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Performance of highly irradiated FBK 3D and planar pixel detectors

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Abstract

The High Luminosity upgrade of the CERN Large Hadron Collider (HL-LHC) requires new radiation tolerant silicon pixel sensors. In the case of the CMS experiment, the first layer of pixel detectors will be installed at about 3 cm from the beam line, where an integrated fluence of about $2 \times 10^{16} \mathrm{n_{eq}cm^{-2}}$ (1 MeV equivalent neutrons) is expected (HL-LHC Runs 4 and 5). The first tracker layer will be substituted before the start of HL-LHC Run 6. The 3D concept for silicon pixel sensors presents several advantages with respect to traditional (planar) sensors. Thanks to short anode-to-cathode distances, 3D sensors are much more resistant to radiation damage, making them suitable for use in the inner layer of the future tracker. This paper describes results from beam tests with highly irradiated planar and 3D sensor and RD53A readout chip combinations. RD53A is the first prototype in 65 nm technology developed by the RD53 collaboration for use in HL-LHC pixel detectors. The sensors were made in FBK foundry in Trento, Italy, and their development was done in collaboration with INFN (Istituto Nazionale di Fisica Nucleare, Italy). Both planar and 3D sensors feature a pixel area of $2500\ \mu\mathrm{m}^2$ and an active thickness of 150 μm. The pixel detectors, irradiated to fluences up to $2.4 \times 10^{16} \mathrm{n_{eq}cm^{-2}}$, were tested in the DESY test beam facility and the analysis of the data shows excellent performances even for the highest irradiation fluences. All results are obtained in the framework of the CMS R&D activities.

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Performance of highly irradiated FBK planar and 3D pixel detectors

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Abstract

The High Luminosity upgrade of the CERN Large Hadron Collider (HL-LHC) requires new radiation tolerant silicon pixel sensors. In the case of the CMS experiment, the first layer of pixel detectors will be installed at about 3 cm from the beam line, where an integrated fluence of about $2 \times 10^{16} n_{eq} cm^{-2}$ (1 MeV equivalent neutrons) is expected (HL-LHC Runs 4 and 5). The first tracker layer will be substituted before the start of HL-LHC Run 6. The 3D concept for silicon pixel sensors presents several advantages with respect to traditional (planar) sensors. Thanks to short anode-to-cathode distances, 3D sensors are much more resistant to radiation damage, making them suitable for use in the inner layer of the future tracker. This paper describes results from beam tests with highly irradiated planar and 3D sensor and RD53A readout chip combinations. RD53A is the first prototype in 65 nm technology developed by the RD53 collaboration for use in HL-LHC pixel detectors. The sensors were made in FBK foundry in Trento, Italy, and their development was done in collaboration with INFN (Istituto Nazionale di Fisica Nucleare, Italy). Both planar and 3D sensors feature a pixel area of 2500 μm^2 and an active thickness of 150 μm. The pixel detectors, irradiated to fluences up to $2.4 \times 10^{16} n_{eq} cm^{-2}$, were tested in the DESY test beam facility and the analysis of the data shows excellent performances even for the highest irradiation fluences. All results are obtained in the framework of the CMS R&D activities.

1. Overview

Pixel detectors in the innermost tracker layer of the CMS experiment during the High Luminosity phase of the Large Hadron Collider (HL-LHC) will have to withstand a fluence of $2 \times 10^{16} n_{eq} cm^{-2}$ (1 MeV equivalent neutrons) while preserving high tracking efficiency [1].

Two different technological solutions are available: planar sensors, where the electrodes are parallel to the sensor surface, and 3D sensors, where the electrodes are orthogonal to the sensor surface. In the first case the distance between electrodes is fixed by the sensor's active thickness, in the second case the distance between electrodes is usually shorter than the sensor thickness. The pixel cell size will be 25×100 μm^2, in order to have a good spatial resolution, while the total active sensor thickness will be 150 μm in order to keep both the bias voltage and the power dissipation after irradiation at a manageable level, while at the same time allowing for a reasonable amount of collected charge to reach full hit detection efficiency. Radiation damage reduces the effective drift distance of charge carriers because of charge trapping, so it is not useful, in the case of planar sensors, to increase the thickness beyond the above limit.

In 3D pixel sensors charge carriers have to travel distances much shorter than the sensor thickness (only 50 μm for a 25×100 μm^2 pixel pitch).

The planar pixel sensors studied in this paper were fabricated at the FBK foundry in Trento and were developed in collaboration with INFN (Istituto Nazionale di Fisica Nucleare, Italy). The substrates selected are p-type Si-Si Direct Wafer Bond (DWB). The 3D pixel sensors studied in this paper were also fabricated at FBK and were developed by the same collaboration that developed the planar sensors [2]. The DWB technique was employed for the substrates. Columnar electrodes of both p^+ and n^+ types are etched by Deep Reactive Ion Etching (DRIE) in the wafer using the Stepper-and-Repeat photo-lithographic technology (with a single-sided process). The 3D sensors studied in this paper come from two FBK productions: Stepper-1 and Stepper-2. The pixel design is the same in the two productions, however in Stepper-2 the distance between n^+ columns and the backside of the sensors was increased.

After fabrication, the pixel sensor wafers (both planar and 3D) were processed for UBM (Under Bump Metallization), thinned, diced and bump-bonded to RD53A prototype readout chips [3] at IZM (Berlin, Germany). The sensor plus chip assembly is referred to as pixel module in the following.

In order to verify that both the sensor and the readout chip are able to withstand the high fluences expected at the HL-LHC with a minimum loss of performance, pixel modules are usually tested before and after irradiation. The pixel modules studied in this paper were irradiated at the KIT Irradiation Centre in a 23 MeV proton beam, to estimated fluences up to 24×10^{16} n_{eq}/cm^2, corresponding to a total ionizing dose of about 30 MGy.

The pixel modules were tested at the DESY Test Beam Facility [4]. The test beam area is equipped with an EUDET-type pixel beam telescope (DATURA), which allows the tracking of beam particles [5]. The telescope is composed of upstream and downstream arms, each consisting of three detector planes. The tested pixel module is placed between the two arms.

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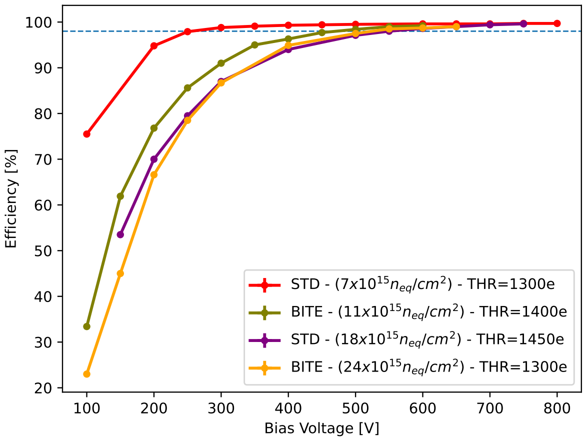

Figure 1: Hit detection efficiencies of the irradiated planar pixel modules versus the applied bias voltage with orthogonal beam incidence. The horizontal dashed line represents 98% efficiency.

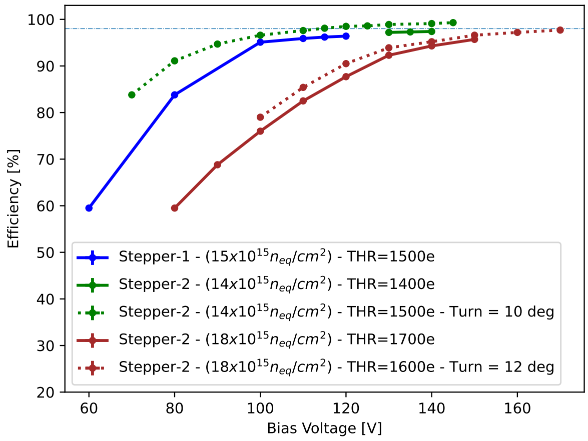

Figure 2: Hit detection efficiencies of the irradiated 3D pixel modules versus the applied bias voltage with orthogonal beam incidence. The horizontal dashed line represents 98% efficiency.

2. Irradiated Planar Pixel Modules

Four irradiated 25×100 µm^2 planar pixel modules were operated in the telescope. Two of the modules have “bitten” implants, meaning that the n$^+$ implant is slightly reduced in relation to the bump pad and the metal layer of the neighbour pixel. This particular design aims to reduce the cross-talk effect, since the bump pad and the implant of neighbour pixels do not overlap. The remaining two modules have standard, non-bitten implants. All the modules were irradiated at KIT at increasing fluences: from 7.5×10^{15} to 24×10^{15} n_{eq}/cm^2.
The modules were tuned to average pixel thresholds ranging from 1300 electrons to 1450 electrons (with a dispersion of about 50 electrons), depending on the module. The tuning was made targeting low thresholds and noise, having at most 1% noisy pixel channels.
Figure 1 shows the hit detection efficiency for the four irradiated modules, as a function of the bias voltage. The efficiency of the module irradiated at a fluence of 11×10^{15} $n_{eq}cm^{-2}$ is greater than 98% around 400 V, while for the module irradiated at 24×10^{15} n_{eq}/cm^2, bias voltages greater than 600 V are necessary.
These studies show that planar pixel modules could survive in the innermost CMS tracker layer during the HL-LHC Runs 4 and 5 (corresponding to 2200 fb^{-1}). However, very high bias voltages are necessary: cooling becomes challenging, especially in the innermost tracker layer. For this reason, 3D pixel sensors are now the baseline option for the innermost layer of the future CMS tracker.

3. Irradiated 3D Pixel Modules

Three irradiated 25×100 µm^2 3D pixel modules were tested on beam: one is from the Stepper-1 production and two are from the Stepper-2 production.
The modules were tuned to average pixel thresholds ranging from 1400 electrons to 1700 electrons (with a dispersion of about 50 electrons), depending on the module.
Figure 2 shows the hit detection efficiency for the irradiated modules, as a function of the bias voltage. The hit detection efficiency of the module irradiated at a fluence of 15×10^{15} $n_{eq}cm^{-2}$ is greater than 98% around 110 V, while for the module irradiated at 18×10^{15} n_{eq}/cm^2 a bias voltages greater than 160 V is necessary.
Since the columns are made by passive material, when the beam is orthogonal to the module the hit detection efficiency is lower at the column boundaries. The dotted lines in Figure 2 report the hit detection efficiencies of the tested modules when they are rotated (by an angle of about 10°) with respect to the beam: the efficiency is slightly higher with respect to the orthogonal beam incidence condition, since in this case the incident particles escape the passive material.
The far lower bias voltages (with respect to planar modules) required to operate these highly irradiated 3D modules, show the effectiveness of the 3D concept.
An increase in the number of noisy channels was observed at high bias voltages (greater than 130-170 V, depending on the module). The problem was more severe with the Stepper-1 module (> 10% of pixel channels). The cause is still under investigation: it could be related to the very high dose (the readout chip was certified to resist only up to 5 MGy).

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