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Ultra-Fast Silicon Detectors for CMS Phase II upgrade

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Summary. — The Minimimum Ionizing Particle Timing Layer (MTD), proposed for the CMS Phase II upgrade at the High Luminosity LHC, will be provided with Ultra-Fast Silicon Detectors (UFSD), that will be covering an area of $\sim 15\ \mathrm{m}^2$ in the pseudorapidity region $1.5 < |\eta| < 3$. MTD has the aim of adding timing information to reconstructed tracks with a precision of $\sim 30\,\mathrm{ps}$: UFSD are the suited technology to reach the goal. In this work, the improvements in the development of such large area detector are presented, highlighting the current status and the R&D process towards the final design.

1. – Time measurements at High Luminosity LHC

At the High Luminosity LHC instantaneous luminosity will increase by a factor of 5 with respect to the LHC case. As a consequence, the number of concurrent events in each bunch crossing will be of the order of 140–200 and vertices will be too close to each other in space to be correctly identified by tracking detectors. In order to cope with this environment and maintain the LHC reconstruction precision, timing information will be added with a resolution of $\sim$30 ps.

In particular, CMS will install a Minimum Ionizing Particle (MIP) Timing Detector (MTD) in the barrel and the endcap regions to preserve its efficiency, resolution and background rejection [1]. Regarding the Endcap Timing Layer (ETL), particular requirements are needed with the aim of maintaining CMS performances at LHC: i) an excellent gain uniformity for large sensors, with a spread in doping smaller than 1%, ii) devices resistant to high radiation fluences, up to $2 \times 10^{15}\ \mathrm{n}_{eq}/\mathrm{cm}^2$, and iii) a coverage higher than 85% for each ETL disk.

2. – The Endcap Timing Layer sensors

Ultra-Fast Silicon Detectors (UFSD) have been chosen to instrument the CMS ETL. These devices are the result of a project born in Torino (INFN and University) in collaboration with the Fondazione Bruno Kessler and the University of Trento. UFSD have the capability to reach the excellent time resolution of ∼30 ps, exploiting the enhanced signals from silicon detectors with moderate internal gain (10–30) provided by the Low-Gain Avalanche Diode (LGAD) technology. Radiation hardness studies have shown the possibility to use these sensors up to fluences of $\sim 3 \times 10^{15}$ n_{eq}/cm^2 while keeping good timing performances [2].

The final sensor for the ETL will be a 32×16 matrix of pixels with a $1.3 \times 1.3\,mm^2$ area and 3.4 pF capacitance. This geometry has been chosen considering two main factors: i) the occupancy, that has to be lower than 2%, and ii) the readout electronics, which has to be connected to devices with a small capacitance to fulfill the CMS requirements.

3. – Laboratory measurements and numerical simulation

3˙1. *Uniformity of multipad structures.* – Studies of gain uniformity on large multipad sensors have been performed acquiring the leakage current value at a fixed bias voltage for each pad of different sensors from all the wafers of the UFSD3 production (2018). The 4×24 CMS ETL devices have been tested on wafer by FBK at a bias voltage of 100 V, and only 0.1% of the total number of pads had a value of leakage current higher than 1 μA. For the 5×5 “ALTIROC” matrices, tested in Torino after dicing, the pads with a leakage current higher than 1 μA at 300 V were 0.7% of the total. The results show thus an excellent gain uniformity for the UFSD3 production by FBK [3].

3˙2. *No-gain area studies.* – In order to obtain segmented sensors, the implementation of gain termination structures between pads is needed. These structures introduce the so called “no-gain” area where charge multiplication does not occur, as shown on the left side of fig. 1. This no-gain area has thus been studied with both measurements and simulations for the UFSD3 production by FBK. The right side of fig. 1 shows the collected charge around the no-gain area, obtained with a 1D scan performed with a picosecond laser (1064 nm, 10 μm spot, ∼10 MIP intensity) along the optical window between two pads. The measured no-gain area widths range between 15 and 40 μm considering all the UFSD3 layouts, improving the previous production design (UFSD2), for which the no-gain area was 66 μm. Moreover, experimental data are in agreement with the results from numerical simulations performed with Sentaurus TCAD [4].

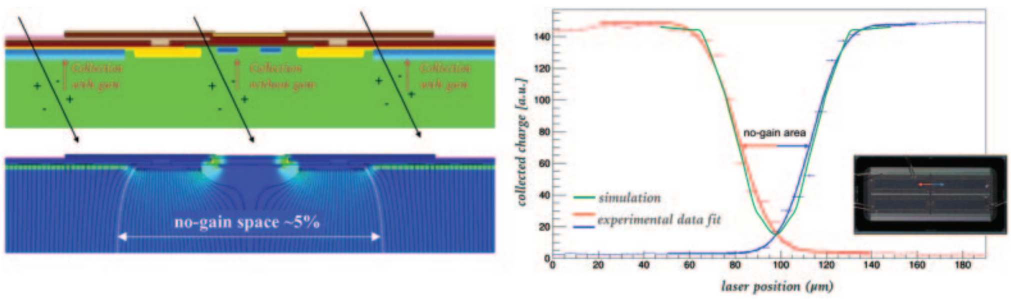

Fig. 1. – Gain termination structures determine the electric field shape in the no-gain area (left). Charge collection in the no-gain area has been studied both with experimental data and simulations (right).

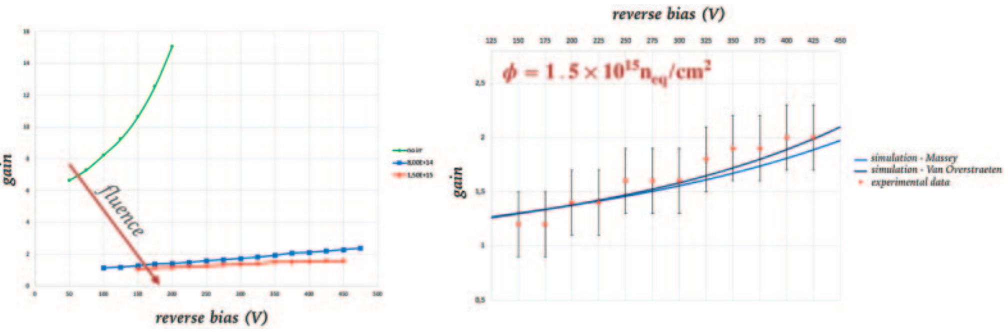

Fig. 2. – Gain curves measured for different fluences (left) and comparison between measurements and simulation for $\phi = 1.5{\times}10^{15}$ n_{eq}/cm^2 (right).

3˙3. *Radiation resistance.* – In a n-in-p device, one of the main effects of radiation damage is the gain layer deactivation, due to the creation of interstitial defects. It has been observed that the addition of carbon in the gain layer allows preventing this phenomenon, since carbon atoms replace boron in interstitial defects. In order to study this effect, sensors have been irradiated at different facilities: some results are here presented for UFSD3 PiN-LGAD pairs irradiated at different fluences with reactor neutrons in Ljubljana [5]. The left plot in fig. 2 shows how the gain curve changes for a non-carbonated detector as a result of the deactivation of the gain layer with increasing radiation fluences. On the right, experimental data for $\phi = 1.5 \times 10^{15}$ n_{eq}/cm^2 can be compared and found in agreement with results obtained with numerical simulation, using both Massey and Van Overstraeten models, differing for the definition of the ionization coefficient.

4. – Conclusions

Ultra-Fast Silicon Detectors have been chosen to instrument the CMS ETL at the High-Luminosity LHC. Measurements show that the third UFSD production by FBK has an excellent yield, between 99.3% and 99.9% depending on the device geometry. The no-gain area width ranges between 15 and 40 μm, improving the previous production design. Additionally, studies on irradiated carbonated sensors show a radiation resistance up to fluences of 3×10^{15} n_{eq}/cm^2.

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