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Characterization of innovative pixel detectors with 3D technology

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Summary. — During the high luminosity runs of the LHC collider, the detectors will face great challenges due to the increase in the particle density. Precise time information will be fundamental to maintain good detector performance. In this article, a study of the characteristics of innovative 3D-trench pixel sensors with precise time measurement is presented. The sensors have been developed at the Fondazione Bruno Kessler in Trento by the TIMESPOT collaboration and the final detector should be capable of 20 ps time resolution, withstanding high radiation doses. In this work, first the static characteristics of the pixel sensors were measured, then their time resolution was studied with a laser system. Next, a sensor was tested with a 2 MeV energy proton beam at the Legnaro National Laboratories AN2000 accelerator facility. The time resolution has been extracted using an innovative time tag system, based on a thin layer of organic scintillator deposited above the detector combined with a Silicon Photomultiplier. The uniformity of the response in the pixel active area has been studied with a precision of a few micrometers. Preliminary results are promising and justify further investigations on the capabilities of these sensors.

1. – Introduction

During the 4th run of LHC, the collider luminosity will increase up to $5 \cdot 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$ and the generation of tracks inside the charge particle detectors of the experiments LHCb, ATLAS, CMS, ALICE will become so high that the pattern-recognition and reconstruction system now available will be slowed down and a great number of ghost tracks will be created, causing inefficient extraction of signals. This work is performed in the context of the TIMESPOT project (TIME and SPace real-time Operating Tracker), which ambitiously aims at developing a complete tracking demonstrator capable of coping with the extremely high instantaneous luminosity foreseen in experiments at future facilities. This demand pushes towards a new concept of vertex detector systems based on 3D technology sensors [1]. Ten INFN sections are involved in the TIMESPOT project (Bologna, Cagliari, Genova, Ferrara, Firenze, Milano, Padova, Perugia, Torino, TIFPA) with 65 people among physicists and engineers.

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2. – The TIMESPOT sensors

Within the TIMESPOT project, radiation hard silicon 3D sensors with pixel size of 55 μm have been developed: they have been optimized for timing measurements while keeping the depletion voltage low and still ensuring good radiation hardness [2]. The electrodes of a fundamental unit of the TIMESPOT 3D silicon sensors have been designed to minimize the terms contributing to the time resolution [3]. As a result, trench-shaped electrodes were chosen: this configuration produces uniform electric and weighting fields and thus allows for the pulse rise time to be largely independent of the hit position. The sensors were produced at the Fondazione Bruno Kessler (FBK) using a single-sided fabrication process. Two batches have been produced so far, one in 2019 (batch 1) and the other in 2021 (batch 2). In batch 2, a p-spray layer is deposited on the surface to insulate the trenches.

3. – Static characterization

The static characterization of the sensors consists in the study of the current-voltage (I-V) and capacitance-voltage (C-V) characteristics. The former is relevant in order to extrapolate the breakdown voltage of the silicon devices, but also to investigate defects in the sensors which could lead to high leakage current and to establish the current that the bias voltage supply should deliver. The latter allows extracting the bias voltage at which the silicon sensor is fully depleted.

3˙1. *I-V characteristics.* – Figure 1, left, displays the I-V characteristics for the strip device number 392 from batch 1 and batch 2 respectively. The presence of the p-spray layer in batch 2 implies that the leakage current is two order of magnitude smaller if compared to the batch 1 devices, since its presence makes the n^+-doped readout electrodes well isolated. Moreover, breakdown voltages are smaller in absolute value: the p-spray layer induces locally high electric field which implies early breakdown, which appears to be around -70 V in the case of batch 2 devices, compared to the -200 V of batch 1 ones.

3˙2. *Irradiation with X-rays.* – To investigate the effect of ionizing radiation on 3D-trenched sensors, a device composed of several silicon strips from batch 2 was irradiated with an X-ray source with energy spectrum peaked at 10 keV at the INFN-PADOVA laboratories. The irradiation was performed in steps and, after each step, the respective I-V characteristics were recorded. Irradiation typically generates positive charges in the surface oxide.

Figure 1, centre, displays the I-V characteristic of strip A from device number 351. After subsequent irradiation, the breakdown voltage increases in absolute value, which means that the positive charges created in the oxide by the irradiation are able to partially compensate the negative charges present in the p-spray. Another effect is the increase of the leakage current: this is due to the contribution of surface currents produced by the electrons released from the silicon dioxide.

3˙3. *C-V characteristics.* – Figure 1, right, displays the C-V characteristics for the strip device number 392 from batch 1 and batch 2 respectively. In the case of the device from batch 1, there is a sudden depletion around $V_{bias} = -25$ V that is due to complex MOS effects. In the case of the batch 2 sensor, the C-V characteristics is more regular, showing a small step around $V_{bias} = -45$ V that can be interpreted as the depletion of the junction induced by the presence of the p-spray layer.

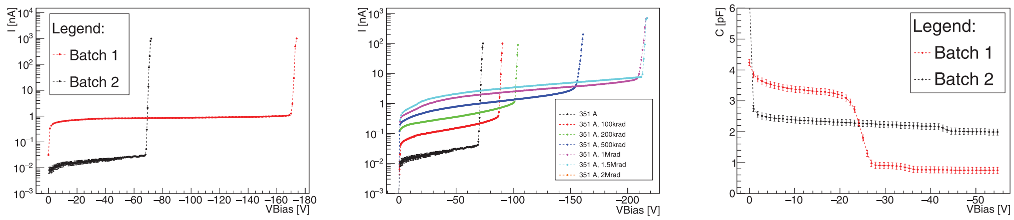

Fig. 1. – Comparison of the *I*-*V* and *C*-*V* characteristics for strip 392 (left and right) and *I*-*V* characteristics of strip 351 after subsequent irradiation with X-rays (centre).

4. – Dynamic characterization

4˙1. *Test-beam at Legnaro National Laboratories.* – The other aim of this work is to characterize the signals produced by the 3D devices in order to estimate the time resolution and the uniformity of the response across the sensor active area. To do so, a dedicated setup was designed and built with the final goal of performing a test-beam at the AN2000 accelerator in Legnaro.

The purpose of the test-beam was to irradiate a strip device with protons of 2 MeV energy: thanks to the micro-beam facility it has been possible to know the hit position of the proton with a precision of 1μ m, allowing to relate the signals to a certain area of the strip. A 2 MeV proton is expected to penetrate the silicon device for $\approx 40\,\mu$m before losing all its energy.

The idea of the physical mechanism considered to perform the time resolution measurement on the TIMESPOT devices is the following. First, a layer of $\approx 10\,\mu$m of P-terphenyl [4], an organic scintillator, is deposited right above the strip to be investigated. Then, a Silicon Photo-Multiplier (SiPM) is placed facing the strip. With this configuration, before the proton hits the strip, it ionizes the scintillator layer, which emits photons that can be revealed by the SiPM. Figure 2, left, displays the setup and its components.

Figure 2, centre, displays the results obtained during the test-beam: looking at the bi-dimensional plot in the box showing the frequency of the trigger on the strip signal, the sensitive area of the strip is highlighted as expected. The SiPM and strip waveforms were recorded by means of a LecroyWavePro 254HD, 2.5 GHz High Definition Oscilloscope (20 GS/s). Analyzing the data offline, a fit of the waveforms was performed with the function:

$$f(t) = b_0 \qquad \text{if } t \le t_0, \qquad b_0 + A \cdot e^{t/\tau_F}(1 - e^{t/\tau_R})/N \qquad \text{if } t > t_0.$$

The parameter t_0 was taken as the pulse reference time. The difference between the SiPM and strip reference times is displayed in fig. 2, centre: the standard deviation of the distribution gives an estimation of the time resolution (σ_t) of the sensor. The result obtained is $\sigma_t \approx 350$ ps. The strip measured time resolution is less than 50 ps (sect. **4**˙2), so it was concluded that this measurement is dominated by the SiPM contribution to the time resolution.

During the final part of the test beam, after each proton irradiation, an *I*-*V* characteristic of the strip device was recorded. After each irradiation, the breakdown voltage becomes closer to zero as a consequence of the irradiation damage (fig. 2, right). Once the breakdown voltage is reached, the leakage current grows with a linear trend due to the resistance placed in the electronic board. Another *I*-*V* characteristics was taken one month after the irradiation (fig. 2, right): comparing it with the last step irradiation

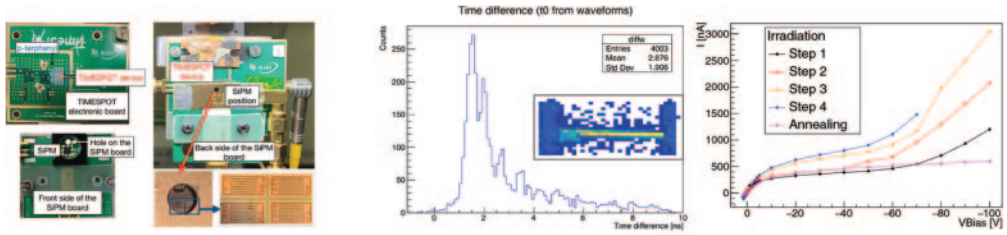

Fig. 2. – Test-beam at Legnaro National Laboratories: experimental setup (left), strip-SiPM time difference distribution and frequency of trigger in the strip plane (centre), strip I-V characteristics after subsequent proton irradiation (right).

characteristic, there is visible annealing, since the breakdown voltage became higher than 100 V in absolute value.

4·2. *Characterization with laser*. – The SiPM and strip time resolution was also extrapolated separately with a dedicated setup simulating the test-beam conditions by means of a fast blue laser with a 40 ps pulse. Concerning the SiPM time resolution, for pulses of the order of the test-beam ones (few millivolts), the SiPM contribution is dominant and of the order of $\approx$400 ps. Regarding the strip, it was observed that this kind of sensors can reach a time resolution of the order of 10 ps if a proper bias voltage is delivered.

5. – Conclusions

In the context of the TIMESPOT project, 3D-trenched electrode silicon sensors with timing precision of the order of 10 ps and high radiation resistance have been fully characterized, in order to find the best design, ensuring the highest breakdown voltage possible, low leakage currents and low capacitance.

Also a dynamic characterization of a 3D strip has been performed, first using a fast laser, finding a time resolution of the order of 10 ps, then using a 2 MeV-proton beam at the AN2000 accelerator in Legnaro. The data collected during the test beam did not allow measuring the strip time resolution due to limits of the setup.

In conclusion, the TIMESPOT 3D sensors demonstrated to be efficiently working, being a possible solution for the need of precise timing information that will arise with the next generation LHC experiments.

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