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Characterization of large LGAD sensors for proton counting in particle therapy

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ABSTRACT: A proton counter prototype based on Low Gain Avalanche Diode (LGAD) technology was developed for the online monitoring of the fluence rate of therapeutic proton beams. The laboratory characterization of LGAD sensors segmented in strips covering an area of 2.6×2.6 cm^2 and the signals produced when single protons delivered at the National Center for Oncological Hadrontherapy (CNAO, Pavia, Italy) cross the sensor will be reported and discussed in this paper. The LGAD sensors are segmented into 146 strips (114×26214 μm^2, 180 μm pitch, and a nominal distance between gain layers of 66 μm). Two strips in one edge are without gain, while all the remaining strips feature a moderate gain. The production included 14 wafers with different characteristics, designed and produced at Fondazione Bruno Kessler (FBK) of Trento in 2020. The laboratory characterization was carried out at FBK, right after production, and at the University of Torino, after cutting the sensors using a probe station with a power analyzer for the static DC electrical tests. The static electrical tests proved that the production of the MoVe-IT-2020 sensors was of very high quality. From 16 sensors randomly selected from different wafers, we observed a consistent correlation between the measurements performed at FBK and the University of Torino, showing that the cut did not affect the yield production. For the first time, LGAD sensors with a large sensitive area able to cover the entire beam spot at the isocenter were tested with clinical proton beams at CNAO. The results showed good separation between signal and noise in the LGAD strip, a feature not seen on the PiN. These results were promising and, in the future, will allows counting properly the protons by selecting the optimal signal threshold.

KEYWORDS: LGAD; Silicon; Laboratory characterization; Large detectors.

Contents

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1. Introduction

Fulfilling the requirements and the ambitious goals of the interdisciplinary INFN project called MoVEIT[1] (Modeling and Verification for Ion beam Treatment planning), the University and the National Institute for Nuclear Physics (INFN) of Torino developed a prototype of a proton counter for the online monitoring of the fluence rate of therapeutic proton beams [1]. It is based on Low Gain Avalanche Detectors (LGAD) [2] segmented in strips to reduce the particle rate per channel. The overall goal is to investigate a new technology based on silicon detectors to overcome the limitation of the ionization chambers currently used for beam monitoring in hadrontherapy [3]. The counter prototype will directly count individual protons at high rates (up to 10^8 p/s*cm^2) with an error below 2 % over an area of 2.6×2.6 cm^2. The laboratory characterization of the sensor production and the preliminary results of a beam test will be reported and discussed in this paper.

2. Materials and Methods

As shown in Fig. 1a each wafer includes eight large sensors designed for the proton counter prototype, each with an area of 2.6×2.6 cm^2 covering the entire beam spot at the isocenter (Fig. 1b; for example, in the CNAO treatment rooms, the proton beam FWHM ranges between 0.7 and 2.2 cm in the clinical energy range [4]). They are segmented in 146 strips (Two strips in one edge are without gain, while all the remaining strips feature a moderate gain) with a sensitive area of 114×26214 μm^2, and a pitch of 180 μm as shown in Fig. 1c. In one of the eight sensors the gain layer was not implanted. The sensors' structures in this production are based on the optimized parameters as determined in the second UFSD production at the Fondazione Bruno Kessler (FBK, Trento, Italy) [5,6] with a distance between gain layers equal to 66 μm. There are other types of sensors in this production with alternative geometries, most of them included for test purposes.
The entire production includes 14 wafers subdivided into three groups on the base of the wafer substrate and nominal gain. The acceptor dopant used for the gain layer implant is boron, specially processed with a low-diffusion thermal cycle, enriched with a dose of carbon in order to maximize the radiation resistance [6,7].

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[1] https://www.tifpa.infn.it/projects/move-it/

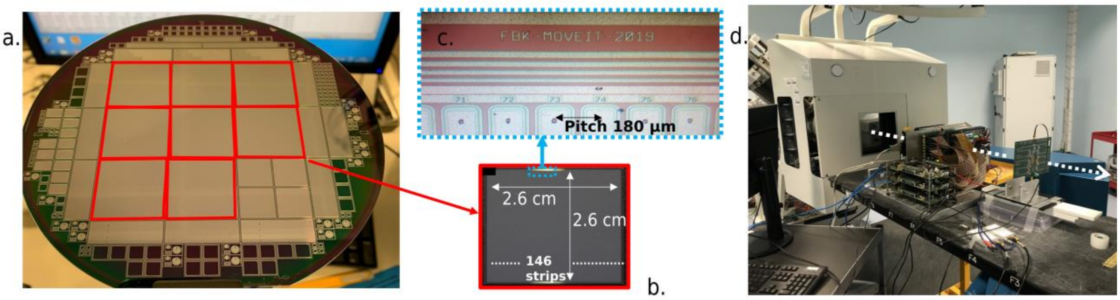

Figure 1. (a) Picture of a wafer; (b) picture of a sensor; (c) magnified image showing the strips surrounded by series of Guard Rings (d) Experimental setup used at CNAO.

The wafers are based on Epitaxial substrates (Epi) with an active thickness of 45 µm (wafers 1, 2, and 14: Group I) and Si-Si substrates for the remaining wafers (3, 4, 5, 6, 7: Group II; 8, 9, 10, 11, 12, and 13: Group III) with an active thickness of 60 µm. Additionally, two doses of boron in the gain implant express in arbitrary unit are used for instance: (Group I: 0.96; Group II: 0.96; Group III: 0.98), where the reduction of gain layer doping concentration that occurs when is enriching this layer with carbon was considered for selecting the doses. More information about the fabrication of Silicon sensors based on LGAD are described by Giacomini in [8].
A characterization of this production in the laboratory was carried out both at the Fondazione Bruno Kessler (FBK, Trento, Italy), and at the University of Torino. The set of measurements are based on the static characteristics of LGAD sensors which consist mainly in Current-Voltage (I-V) measurements [6]. Two sensors with all the strips working properly from wafers 1 and 14 were tested with a clinical proton beam at National Center for Oncological Hadrontherapy (CNAO, Pavia, Italy), as shown in Fig. 1d. The sensors were glued on a PCB designed for housing the digital front-end readout [1]. However, the board allows acquiring the two analog signals from the strip 1 (PiN) and the strip 146 (LGAD), located at the opposite edges of the sensor at a distance of 2.6 cm, thus allowing to perform studies of the signal shape. The sensors of the two boards were aligned along the beam direction and placed at a relative distance of 470 ± 1 mm. The readout of the first board (the closest to the nozzle exit) was based on the digital output of the PCB, and the results are out of the scope of this study. For the second sensor the signals from strip 1 (PiN) and 146 (LGAD) were fed to low-noise current amplifiers (CIVIDEC C2[2] , 40 dB gain and 2 GHz bandwidth) which outputs were collected by a high rate digitizer (CAEN DT5742[3] , 5GS/s, 12 bits resolution, 1 ADC = 0.24 mV, acquisition windows of 1024 samples, i.e. 204.5 ns) for the offline analysis. The analog signal shape was studied with the lowest beam energy of 62.28 MeV provided by the facility. The reason for this choice was to maximize the rate of protons hitting the two strips by selecting the beam energy providing the maximum pencil beam FWHM, 2.2 cm in air at the isocenter [4].

3. Results and Discussion

The production yield and wafer uniformity were measured at FBK right after production using a dedicated probe card with 24 channels. The whole production, corresponding to 112 detectors and 16352 strips, was tested. The criteria to define a bad strip were the following: a bad strip can either not reach 160 V or has more than 0.5 µA at 160 V. Good sensor are those without bad strips. The results were grouped by the three groups of wafers with similarity characteristics and fitted with a Gaussian distribution where the coefficient of determination was greater than 85% for all cases. Wafer 9 shows a different behavior compared to wafers 8, 10, 11, 12, and 13, which nominally have the same characteristics. The mean leakage current for Wafer 9 is found 2.1 times larger than the other wafers of group III. This could be due to a systematic error probably related to different temperatures during the test. A more detailed investigation is

[2] https://cividec.at/electronics-C2.html
[3] https://www.caen.it/products/dt5742/

needed in group III to understand such a difference. The ratio between 90/10 percentiles was lower than 1.62 for all the cases, showing a good uniformity. It was observed a percentage of good strips and good sensors of 87.3, 39.8 and 99.8, 85.7 for LGAD and PiN, respectively. In total, of the 112 detectors measured, 51 were good sensors (45.54 %). It is important to point out that even the relatively low yield is expected considering the large area of the detectors.

The full depletion voltage was measured using the I-V curve at the University of Torino after cutting the wafers with two methods: the first makes use of a probe card with 40 needles, produced by Technoprobe[4], and the second method exploits a conductive polymer (elastomer) to perform a single measurement that includes all the strips and the Guard Ring of the sensor [9]. The mean depletion voltage for group III is 23 $\pm$ 2 V and for group II is 22 $\pm$ 2 V. The reason for this difference is mainly the gain layer because group III has a gain layer 2 % more doped than group II. For group I, the full depletion voltage is 35 $\pm$ 4 V, and it is higher than the reported full depletion voltage for group II and III. The difference is because the Epi wafers have a substrate with lower resistivity, which translates in additional bias voltage with respect to the Si-Si needed to fully deplete the device. A group of 16 sensors was randomly selected among good and bad sensors, and the outcomes were compared from both institutions (FBK, UNITO) in order to verify the effect of cutting the sensors. The selection criteria applied at FBK were applied again to the selected group of sensors at the University of Torino. A good match between the two sets of measures was observed where only 1 strip from the 2336 strips analyzed had different behavior, thus confirming that the cut did not affect the yield of the production.

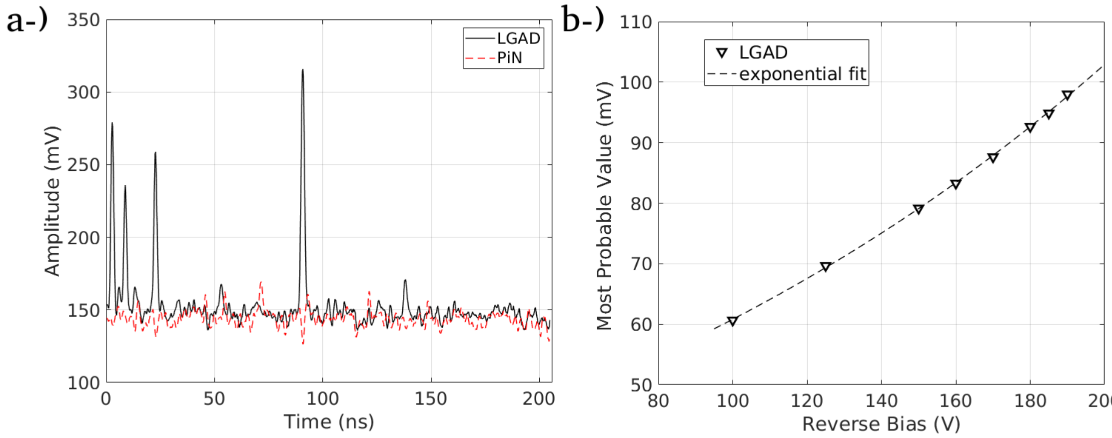

Figure 2. (a) Signals produced by 62.28 MeV protons in 45 μm thick strips silicon detector. (b) Most Probable Value *vs.* Reverse Bias for the LGAD strip.

Fig. 2a shows the signal produced in the two strips by 62.28 MeV protons using a reverse bias voltage of 190 V in a time window of 205 ns. A signal duration of about 3 ns was measured. As can be observed, good separation between signal and noise can be achieved in the LGAD strip by choosing a proper threshold while for the strip without gain the signal has almost the same amplitude as the noise, therefore , it is difficult to separate it from the noise level. It has to be noticed that an additional noise was measured during the beam irradiation, which is induced by particles crossing the neighbor strips in the whole sensors: this effect will be studied in the future. The measurements were performed as a function of the bias voltage, as shown in Fig.2b. As expected, increasing the bias voltage, the Most Probable Value (MPV) follows an exponential behavior due to the presence of the gain layer. The noise standard deviation in the inter-spill was between 4-5 mV for all the bias voltage used, which implies in a signal-to-noise ratio around 15-20.

[4] https://www.technoprobe.com/

4. Conclusion

A production of large (2.6×2.6 cm^2) thin silicon LGAD sensors segmented in strips dedicated to beam monitoring applications were produced at FBK and tested in the laboratory before cutting at FBK and after cutting at the Physics Department of the University of Torino confirming that the cut did not affect the yield of the production. The static electrical tests proved that the production of the MoVe-IT-2020 sensors was of very high quality. For the first time, LGAD sensors with a large sensitive area able to cover the entire beam spot at the isocenter were tested with clinical proton beams at CNAO. The results showed good separation between signal and noise in the LGAD strip, a feature not seen on the PiN. These outcomes were very promising and, in the future, will allows counting properly the protons by selecting the optimal signal threshold.

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