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1 Characterization of large LGAD sensors for proton 2 counting in particle therapy

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16 **ABSTRACT:** A proton counter prototype based on Low Gain Avalanche Diode (LGAD) technology
17 was developed for the online monitoring of the fluence rate of therapeutic proton beams. The
18 laboratory characterization of LGAD sensors segmented in strips covering an area of 2.6×2.6
19 cm² and the signals produced when single protons delivered at the National Center for
20 Oncological Hadrontherapy (CNAO, Pavia, Italy) cross the sensor will be reported and
21 discussed in this paper. The LGAD sensors are segmented into 146 strips (114×26214 μm²,
22 180 μm pitch, and a nominal distance between gain layers of 66 μm). Two strips in one edge
23 are without gain, while all the remaining strips feature a moderate gain. The production included
24 14 wafers with different characteristics, designed and produced at Fondazione Bruno Kessler
25 (FBK) of Trento in 2020. The laboratory characterization was carried out at FBK, right after
26 production, and at the University of Torino, after cutting the sensors using a probe station with a
27 power analyzer for the static DC electrical tests. The static electrical tests proved that the
28 production of the MoVe-IT-2020 sensors was of very high quality. From 16 sensors randomly
29 selected from different wafers, we observed a consistent correlation between the
30 measurements performed at FBK and the University of Torino, showing that the cut did not
31 affect the yield production. For the first time, LGAD sensors with a large sensitive area able to
32 cover the entire beam spot at the isocenter were tested with clinical proton beams at CNAO.
33 The results showed good separation between signal and noise in the LGAD strip, a feature not
34 seen on the PiN. These results were promising and, in the future, will allow counting properly
35 the protons by selecting the optimal signal threshold.

36
37 **KEYWORDS: LGAD; Silicon; Laboratory characterization; Large detectors.**

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48 **1. Introduction**

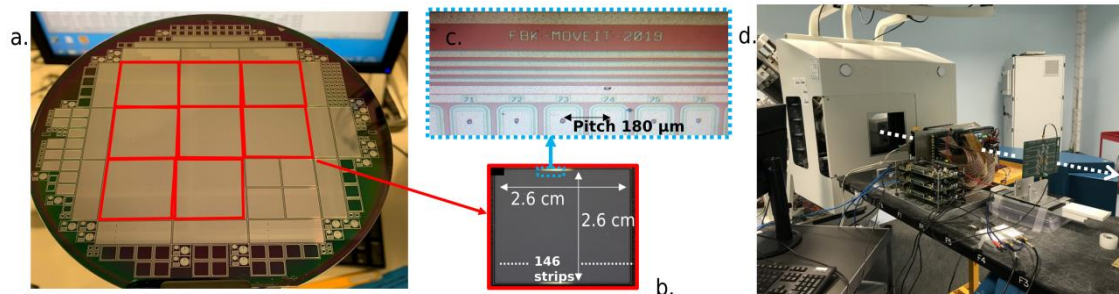
49 Fulfilling the requirements and the ambitious goals of the interdisciplinary INFN project called
50 MoVEIT¹ (Modeling and Verification for Ion beam Treatment planning), the University and the
51 National Institute for Nuclear Physics (INFN) of Torino developed a prototype of a proton
52 counter for the online monitoring of the fluence rate of therapeutic proton beams [1]. It is based
53 on Low Gain Avalanche Detectors (LGAD) [2] segmented in strips to reduce the particle rate per
54 channel. The overall goal is to investigate a new technology based on silicon detectors to
55 overcome the limitation of the ionization chambers currently used for beam monitoring in
56 hadrontherapy [3]. The counter prototype will directly count individual protons at high rates (up
57 to 10^8 p/s*cm²) with an error below 2 % over an area of 2.6×2.6 cm². The laboratory
58 characterization of the sensor production and the preliminary results of a beam test will be
59 reported and discussed in this paper.

60 **2. Materials and Methods**

61 As shown in Fig. 1a each wafer includes eight large sensors designed for the proton counter
62 prototype, each with an area of 2.6×2.6 cm² covering the entire beam spot at the isocenter (Fig.
63 1b; for example, in the CNAO treatment rooms, the proton beam FWHM ranges between 0.7
64 and 2.2 cm in the clinical energy range [4]). They are segmented in 146 strips (Two strips in one
65 edge are without gain, while all the remaining strips feature a moderate gain) with a sensitive
66 area of 114×26214 μm², and a pitch of 180 μm as shown in Fig. 1c. In one of the eight sensors
67 the gain layer was not implanted. The sensors' structures in this production are based on the
68 optimized parameters as determined in the second UFSD production at the Fondazione Bruno
69 Kessler (FBK, Trento, Italy) [5,6] with a distance between gain layers equal to 66 μm. There are
70 other types of sensors in this production with alternative geometries, most of them included for
71 test purposes.

72 The entire production includes 14 wafers subdivided into three groups on the base of the wafer
73 substrate and nominal gain. The acceptor dopant used for the gain layer implant is boron,
74 specially processed with a low-diffusion thermal cycle, enriched with a dose of carbon in order
75 to maximize the radiation resistance [6,7].

¹ <https://www.tifpa.infn.it/projects/move-it/>



76

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

79 The wafers are based on Epitaxial substrates (Epi) with an active thickness of 45 μm (wafers 1,
 80 2, and 14: Group I) and Si-Si substrates for the remaining wafers (3, 4, 5, 6, 7: Group II; 8, 9, 10,
 81 11, 12, and 13: Group III) with an active thickness of 60 μm . Additionally, two doses of boron in
 82 the gain implant express in arbitrary unit are used for instance: (Group I: 0.96; Group II: 0.96;
 83 Group III: 0.98), where the reduction of gain layer doping concentration that occurs when is en-
 84 riching this layer with carbon was considered for selecting the doses. More information about
 85 the fabrication of Silicon sensors based on LGAD are described by Giacomini in [8].

86 A characterization of this production in the laboratory was carried out both at the Fondazione
 87 Bruno Kessler (FBK, Trento, Italy), and at the University of Torino. The set of measurements are
 88 based on the static characteristics of LGAD sensors which consist mainly in Current-Voltage (I-
 89 V) measurements [6]. Two sensors with all the strips working properly from wafers 1 and 14
 90 were tested with a clinical proton beam at National Center for Oncological Hadrontherapy
 91 (CNAO, Pavia, Italy), as shown in Fig. 1d. The sensors were glued on a PCB designed for
 92 housing the digital front-end readout [1]. However, the board allows acquiring the two analog
 93 signals from the strip 1 (PiN) and the strip 146 (LGAD), located at the opposite edges of the
 94 sensor at a distance of 2.6 cm, thus allowing to perform studies of the signal shape. The sen-
 95 sors of the two boards were aligned along the beam direction and placed at a relative distance
 96 of 470 ± 1 mm. The readout of the first board (the closest to the nozzle exit) was based on the
 97 digital output of the PCB, and the results are out of the scope of this study. For the second sen-
 98 sor the signals from strip 1 (PiN) and 146 (LGAD) were fed to low-noise current amplifiers
 99 (CIVIDEC C2², 40 dB gain and 2 GHz bandwidth) which outputs were collected by a high rate
 100 digitizer (CAEN DT5742³, 5GS/s, 12 bits resolution, 1 ADC = 0.24 mV, acquisition windows of
 101 1024 samples, i.e. 204.5 ns) for the offline analysis. The analog signal shape was studied with
 102 the lowest beam energy of 62.28 MeV provided by the facility. The reason for this choice was to
 103 maximize the rate of protons hitting the two strips by selecting the beam energy providing the
 104 maximum pencil beam FWHM, 2.2 cm in air at the isocenter [4].

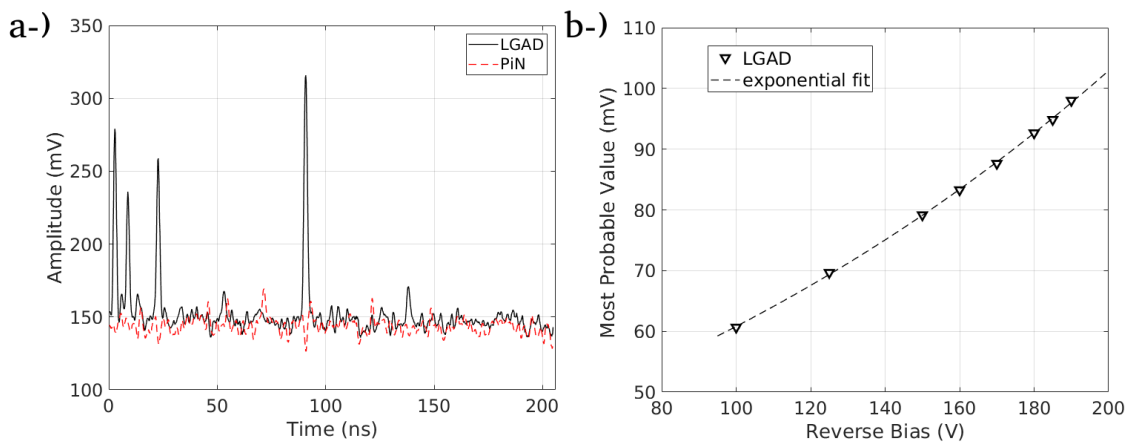
105 3. Results and Discussion

106 The production yield and wafer uniformity were measured at FBK right after production using a
 107 dedicated probe card with 24 channels. The whole production, corresponding to 112 detectors
 108 and 16352 strips, was tested. The criteria to define a bad strip were the following: a bad strip
 109 can either not reach 160 V or has more than 0.5 μA at 160 V. Good sensor are those without
 110 bad strips. The results were grouped by the three groups of wafers with similarity characteristics
 111 and fitted with a Gaussian distribution where the coefficient of determination was greater than
 112 85% for all cases. Wafer 9 shows a different behavior compared to wafers 8, 10, 11, 12, and 13,
 113 which nominally have the same characteristics. The mean leakage current for Wafer 9 is found
 114 2.1 times larger than the other wafers of group III. This could be due to a systematic error
 115 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/>

116 needed in group III to understand such a difference. The ratio between 90/10 percentiles was
 117 lower than 1.62 for all the cases, showing a good uniformity. It was observed a percentage of
 118 good strips and good sensors of 87.3, 39.8 and 99.8, 85.7 for LGAD and PiN, respectively. In
 119 total, of the 112 detectors measured, 51 were good sensors (45.54 %). It is important to point
 120 out that even the relatively low yield is expected considering the large area of the detectors.
 121 The full depletion voltage was measured using the I-V curve at the University of Torino after
 122 cutting the wafers with two methods: the first makes use of a probe card with 40 needles,
 123 produced by Technoprobe⁴, and the second method exploits a conductive polymer (elastomer)
 124 to perform a single measurement that includes all the strips and the Guard Ring of the sensor
 125 [9]. The mean depletion voltage for group III is 23 ± 2 V and for group II is 22 ± 2 V. The
 126 reason for this difference is mainly the gain layer because group III has a gain layer 2 % more
 127 doped than group II. For group I, the full depletion voltage is 35 ± 4 V, and it is higher than the
 128 reported full depletion voltage for group II and III. The difference is because the Epi wafers have
 129 a substrate with lower resistivity, which translates in additional bias voltage with respect to the
 130 Si-Si needed to fully deplete the device. A group of 16 sensors was randomly selected among
 131 good and bad sensors, and the outcomes were compared from both institutions (FBK, UNITO)
 132 in order to verify the effect of cutting the sensors. The selection criteria applied at FBK were
 133 applied again to the selected group of sensors at the University of Torino. A good match
 134 between the two sets of measures was observed where only 1 strip from the 2336 strips
 135 analyzed had different behavior, thus confirming that the cut did not affect the yield of the
 136 production.



137
 138 Figure 2. (a) Signals produced by 62.28 MeV protons in 45 μm thick strips silicon detector. (b) Most
 139 Probable Value vs. Reverse Bias for the LGAD strip.

140
 141 Fig. 2a shows the signal produced in the two strips by 62.28 MeV protons using a reverse bias
 142 voltage of 190 V in a time window of 205 ns. A signal duration of about 3 ns was measured. As
 143 can be observed, good separation between signal and noise can be achieved in the LGAD strip
 144 by choosing a proper threshold while for the strip without gain the signal has almost the same
 145 amplitude as the noise, therefore, it is difficult to separate it from the noise level. It has to be
 146 noticed that an additional noise was measured during the beam irradiation, which is induced by
 147 particles crossing the neighbor strips in the whole sensors: this effect will be studied in the
 148 future. The measurements were performed as a function of the bias voltage, as shown in
 149 Fig.2b. As expected, increasing the bias voltage, the Most Probable Value (MPV) follows an
 150 exponential behavior due to the presence of the gain layer. The noise standard deviation in the
 151 inter-spill was between 4-5 mV for all the bias voltage used, which implies in a signal-to-noise
 152 ratio around 15-20.

⁴ <https://www.technoprobe.com/>

153 **4. Conclusion**

154 A production of large (2.6x2.6 cm²) thin silicon LGAD sensors segmented in strips dedicated to
155 beam monitoring applications were produced at FBK and tested in the laboratory before cutting
156 at FBK and after cutting at the Physics Department of the University of Torino confirming that
157 the cut did not affect the yield of the production. The static electrical tests proved that the
158 production of the MoVe-IT-2020 sensors was of very high quality. For the first time, LGAD
159 sensors with a large sensitive area able to cover the entire beam spot at the isocenter were
160 tested with clinical proton beams at CNAO. The results showed good separation between signal
161 and noise in the LGAD strip, a feature not seen on the PiN. These outcomes were very
162 promising and, in the future, will allow counting properly the protons by selecting the optimal
163 signal threshold.

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