

Proprieties of FBK UFSDs after neutron and proton irradiation up to $6 \cdot 10^{15}$ neq/cm²

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Abstract– The properties of 60- μ m thick Ultra-Fast Silicon Detectors (UFSD) detectors manufactured by Fondazione Bruno Kessler (FBK), Trento (Italy) were tested before and after irradiation with minimum ionizing particles (MIPs) from a ⁹⁰Sr β -source . This FBK production, called UFSD2, has UFSDs with gain layer made of Boron, Boron low-diffusion, Gallium, Carbonated Boron and Carbonated. The irradiation with neutrons took place at the TRIGA reactor in Ljubljana, while the proton irradiation took place at CERN SPS. The sensors were exposed to a neutron fluence of $4 \cdot 10^{14}$, $8 \cdot 10^{14}$, $1.5 \cdot 10^{15}$, $3 \cdot 10^{15}$, $6 \cdot 10^{15}$ neq/cm² and to a proton fluence of $9.6 \cdot 10^{14}$ p/cm², equivalent to a fluence of $6 \cdot 10^{14}$ neq/cm². The internal gain and the timing resolution were measured as a function of bias voltage at -20°C. The timing resolution was extracted from the time difference with a second calibrated UFSD in coincidence, using the constant fraction method for both.

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Keywords: fast silicon sensors; charge multiplication; thin tracking sensors; radiation damage; time resolution.

1 - Introduction

The so-called ultra-fast silicon detector (UFSD) will establish a new paradigm for space-time particle tracking [1]. UFSD are thin pixelated n-on-p silicon sensors based on the Low-Gain Avalanche Detector (LGAD) design [2][3][4] developed by the Centro Nacional de Microelectrónica (CNM) Barcelona, in part as a RD50 Common Project [5]. The sensor exhibits moderate internal gain (~5-70) due to a highly doped p+ region just below the n-type implants. First applications of UFSD are envisioned in the upgrades of the ATLAS and CMS experiments at the High-Luminosity Large Hadron Collider (HL-LHC [10]) as reviewed in [11]. In both experiments, the UFSD would be of moderate segmentation (a few mm²) and will face challenging radiation requirements (fluences up to several 10¹⁵ neq/cm² and several hundred of MRad).

Previous measurements on different kind of LGAD sensors in beam tests and laboratory before and after irradiation are reported in [7][8][19], these results show that the time resolution of LGADs can be lower than 20 ps. These sets of measurements agree well with the predictions of the simulation program Weightfield2 (WF2) [9]. In all cases the timing resolution has been shown to deteriorate with fluence due

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to the decreasing value of the gain. This effect is caused by the acceptor removal mechanism [15][20] that decreases the concentration of the active dopant in the gain layer.

In this paper, we report on the performances of 60- μm thick UFSDs produced by FBK before and after a irradiation: the sensors were exposed to a neutron fluence of $4 \cdot 10^{14}$, $8 \cdot 10^{14}$, $1.5 \cdot 10^{15}$, $3 \cdot 10^{15}$, $6 \cdot 10^{15}$ neq/cm² and to a proton fluence of $9.6 \cdot 10^{14}$ p/cm², equivalent to a fluence of $6 \cdot 10^{14}$ neq/cm².

In Section 2 we will briefly describe the characteristics of the UFSD2 FBK production, already reported in [20]. Section 3 provided the description of the irradiation facilities. In Section 4, a short description of the experimental set-up is presented; details were previously reported in [6], [14] and [19]. In Section 5, we will describe the data analysis including the extraction of the gain and the time resolution, and in Section 6 the results on bias dependence of charge collection and gain, pulse characteristics and timing resolution for a range of fluences will be presented. The performances of the studied UFSDs will be compared.

2 – Properties of the FBK UFSDs W1 through W15

As described in more detail in reference [20] 60-micron thick LGAD sensors with 5 different gain layer configurations have been manufactured at the Fondazione Bruno Kessler: (i) Boron (B), (ii) Boron low-diffusion (B LD), (iii) Gallium (Ga), (iv) carbonated Boron (B+C), and (v) carbonated Gallium (Ga+C). It is important to note that carbon enrichment has been done uniquely in the volume of the gain layer to avoid a sharp increase of the leakage current. A short summary of the UFSD2 production is shown in Table 1: in total 18 wafers were processed, 10 with B-doped and 8 with Ga-doped gain layer. In this paper we present the response to MIP particles of the most important wafers of the production (wafers 1, 6, 8, 14 and 15). All sensors were studied, however some measurements are missing since a few sensors either broke during handling (eg: W1 sensor for $4e14$ neq/cm²) or were not tested completely. From the study of the CV curves, the active doping concentration of the gain layer can be calculated [20]: these studies showed that W6 (B+C) retains the highest fraction of active gain layer doping after a given fluence, followed by W15 (Ga+C), then W1 (B LD), W8 (Boron) and lastly W14 (Ga). The proton fluence is stated in neq/cm² ($6e14$) while the real total fluence is $9.4e14$ p/cm².

Wafer #	Dopant	Gain Dose	N fluence (neq/cm ²)	P fluence (neq/cm ²)
1	B LD	0.98	8e14, 1.6e15, 3e15	6e14
6	B + C	1.02	4e14, 8e14, 1.6e15, 3e15, 6e15	6e14
8	B	1.02	4e14, 8e14, 1.6e15, 3e15, 6e15	
14	Ga	1.04	4e14, 8e14, 1.6e15, 3e15	
15	Ga + C	1.04	4e14, 8e14, 1.6e15, 3e15	6e14

Table 1: Wafers tested with charge collection after the irradiation campaign.

3 – Irradiations

The UFSD were irradiated without bias in the JSI research reactor of TRIGA type in Ljubljana, which has been used successfully in the past decades to support sensor development [17]. The neutron spectrum and flux are well known and the fluence is quoted in 1 MeV equivalent neutrons per cm² (neq/cm² or shortened n/cm²).

A different set of LGADs was irradiated with protons at the IRRAD CERN irradiation facility [21]. The IRRAD proton facility is located on the T8 beam-line at the CERN PS East Hall where the primary proton beam with a momentum of 24 GeV/c is extracted from the PS ring. In IRRAD, irradiation experiments are performed using the primary protons, prior to reach the beam dump located downstream the T8 beam line. After irradiation, the devices were annealed for 80 min at 60 C. Afterward the devices were kept in cold storage at -20 C.

4 – β -telescope setup

The laboratory setup with ^{90}Sr β -source as well as the readout electronics has been previously described in detail in [6], [14]. It is important to note that the system is housed in a climate chamber allowing operations of irradiated sensors at lower temperature down to -27°C . The trigger and time reference is provided by a second HPK UFSD with time resolution of 15 ± 1 ps. The time resolution for the trigger UFSD was measured pairing two identical UFSDs. Following a trigger pulse, the traces of both trigger and DUT were recorded, with a rate around one Hz with a digital scope with an analogue bandwidth of 2.4 GHz and a digitization step of 50 ps.

5 – Data analysis

The data analysis follows the steps listed in [6]; additional details can be found in [14], [18] and [20]. The digital oscilloscope records the full waveform of both trigger and DUT in each event, so the complete event information is available for offline analysis. The normalized average pulse shape for both sensors before and after irradiation for W6 (carbonated Boron) and W8 (Boron only) sensors can be seen in Fig. 1, indicating an increase of the slope of the rising edge for both.

The time of arrival of a particle is defined with the constant fraction discriminator (CFD) method [14] [18], offering a very efficient correction to the time walk effect. The CFD value can be optimized for every bias voltage and fluence to minimize the time resolution, a procedure that is necessary since both the pulse shape and the noise contributions change with fluence. Due to the oscilloscope digitization steps, the time of arrival at a specific CFD fraction is evaluated with a linear interpolation. The event selection is straightforward: for a valid trigger pulse, the signal amplitude, P_{max} , of the DUT UFSD should not be saturated by either the scope or the read-out chain. To eliminate the contributions from non-gain events or noise, the time of the pulse maximum, T_{max} , has to fall within a window of 1 ns centered on the CFD threshold of 20% of the trigger. The DUT time resolution is calculated from the RMS value of the Gaussian fit to the time difference Δt between the DUT and the trigger.

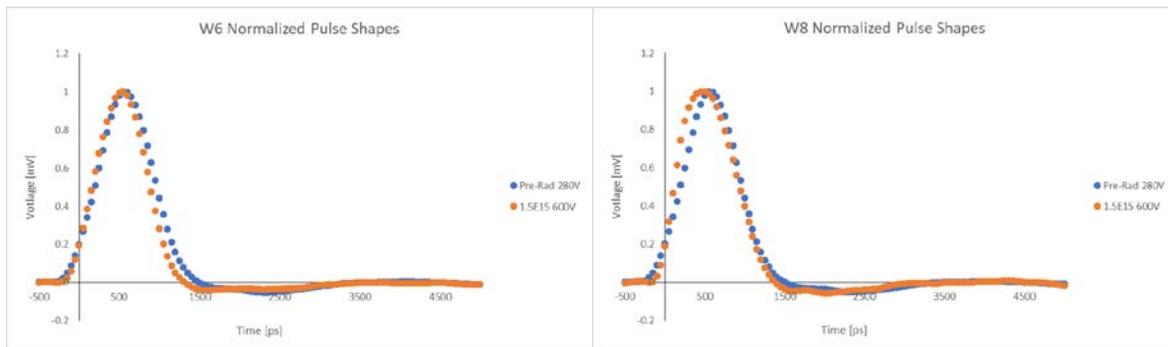


Fig 1: Average normalized pulse shape for W6 (carbonated Boron) (left) and W8 (Boron only) (right) for before and after $1.5\text{E}15$ neq/cm^2 irradiation.

6 - Results

In this section we present a brief description of the most important results obtained so far

6.1 Gain vs bias for different fluences

As observed in previous measurements [14], the value of the gain of UFSD decreases with fluence and can in part be recovered by increasing the bias voltage applied to the sensor, as shown in Fig. 2. For UFSD2 sensors, this decrease is less or more pronounced for the different types of gain layer doping. Fig. 3 shows the maximum operating voltage for sensor after irradiation, defined as the maximum bias voltage that can be applied to the sensor before breakdown. All measurements for irradiated sensors were taken at -20°C , while for not irradiated sensors at 20°C .

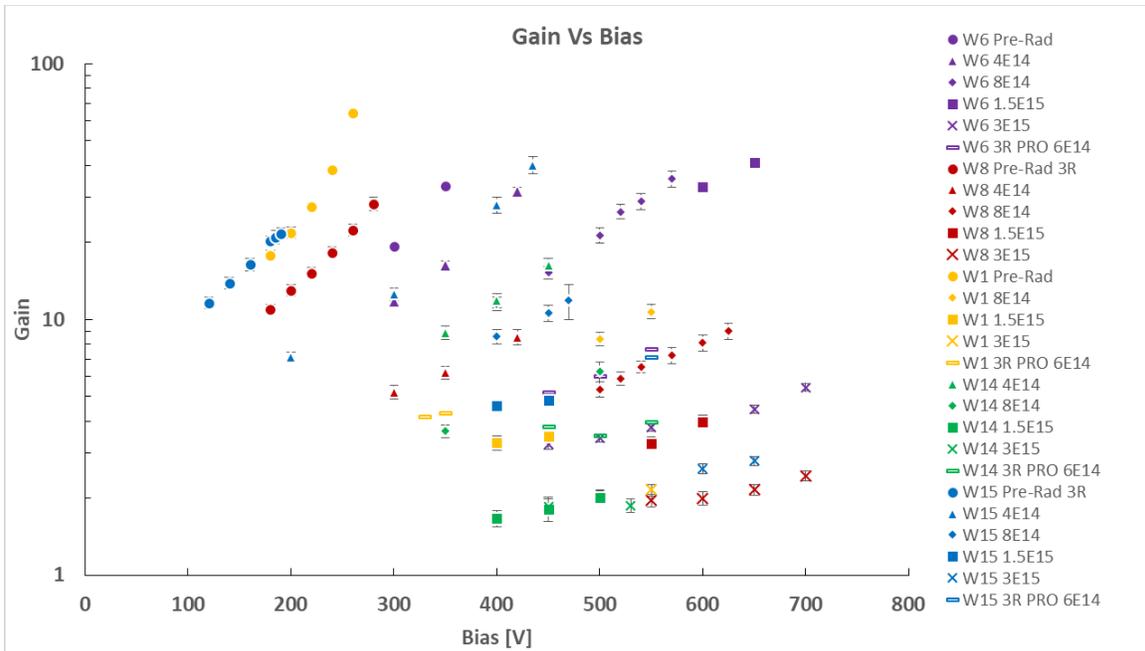


Fig 2: Gain as a function of bias voltage applied.
W1 (Boron LD) W6 (Boron carbon) W8 (Boron) W14 (Gallium) W15 (Gallium carbon)

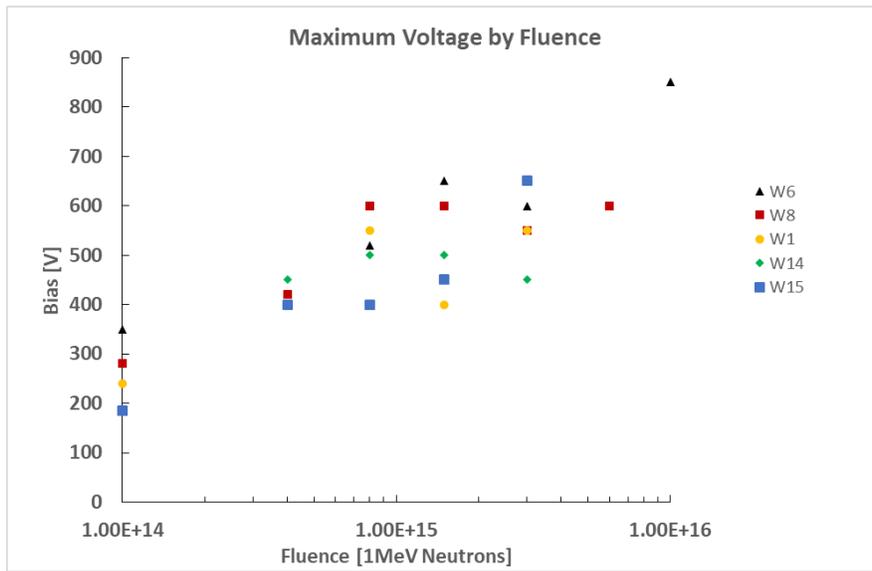


Fig 3: Maximum operating voltage for different fluences.
W1 (Boron LD) W6 (Boron carbon) W8 (Boron) W14 (Gallium) W15 (Gallium carbon)
(The values before irradiation are shown at a fluence of 1E14 n/cm²)

6.2 Rise time

An important parameter determining the time resolution is the rise time: for un-irradiated sensors, the rise time is determined by the electron drift time, while for irradiated sensors it becomes shorter as the multiplication mechanism moves from the gain layer to the bulk and the bias voltage increases [14]. The dependence of the rise time (10 – 90%) upon the bias voltage is shown in Fig 4a. For all sensors, the rise time decreases with progressive irradiation.

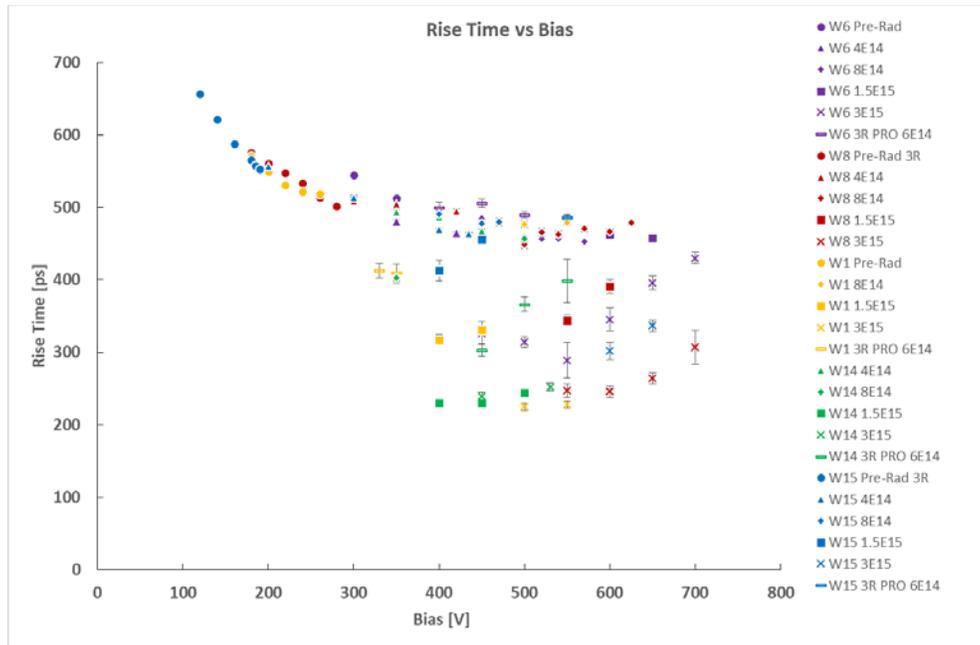


Fig 4a: Rise time (10 - 90%) as a function of bias voltage.
W1 (Boron LD) W6 (Boron carbon) W8 (Boron) W14 (Gallium) W15 (Gallium carbon)

In Fig. 4b, the rise time as a function of gain is shown. For very highly irradiated sensors which exhibit low gain, the rise time increase with increasing gain, before decreasing slightly. This can be explained by the fact that the contribution of the original drifting charge has a faster rise time than the drifting holes from the multiplication process, and thus have a larger influence on the pulse shape at low gain.

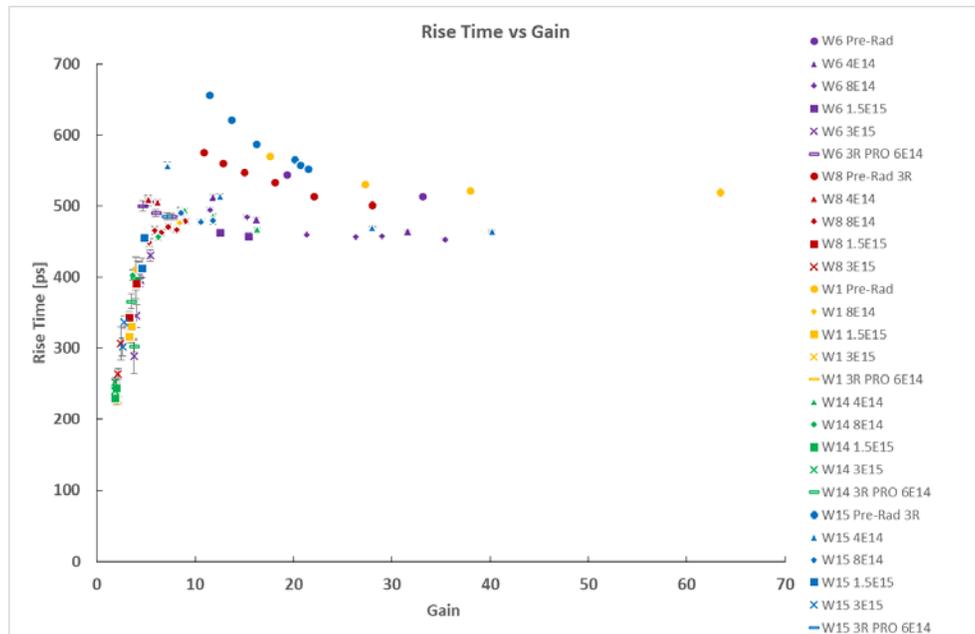


Fig 4b: Rise time (10 - 90%) as a function of gain.
W1 (Boron LD) W6 (Boron carbon) W8 (Boron) W14 (Gallium) W15 (Gallium carbon)

6.3 Time resolution

The time resolution of UFSD of all wafers is roughly the same before irradiation (Fig. 5). This information is very important as it indicates that neither the addition of Carbon nor the presence of Gallium in the gain layer can cause a degradation of performances. Comparing the performances of the different wafers as a function of fluence, evaluated at 20 % CFD, we see that the results of W6 (B+C) are superior to those of all other wafers.

Fig. 6 shows the time resolution as a function of a CFD scan from 10 % to 99 % for W6 and W8 sensors. The difference at a fluence of $1.5E15$ is striking, and shows that for W6 a large fraction of the original gain layer is still active at that fluence, confirming the results from the C-V measurements [20]. In Table 2 the best (“optimized”) CFD and the range (for 10% of time resolution variation from the minimum) for each sensor and fluence is shown. As a function of fluence, the value of CFD needs to be moved to higher values since the Jitter contribution is smaller at higher CFD settings.

This study shows that if the CFD threshold is optimized, the performance of the all wafers improves (Fig. 7). UFSD from wafers W8 (B) and W1 (B LD) have comparable performances to W6 (B+C) using a value of CFD around 50% (70%) for $1e15$ ($3e15$) neq/cm^2 while W6 (B+C) has comparable or better performance with a lower CFD value (20-30%).

At very high fluence ($6e15 neq/cm^2$), the multiplication layer is completely de-activated for every gain layer type, and both W6 and W8 require a very high CFD value (70-75%). All the values showed in the plots are measured at -20 C for irradiated sensors and at room temperature for not irradiated sensors. Some of the sensors were also tested at -27 C but no performance improvements were observed.

W #	Dopant	Dose	Neutron						Proton	
1	B LD	0.98	0	4e14	8e14	1.6e15	3e15	6e15	6e14	fluence (neq/cm^2)
			5		14	52	70		38	Optimal CFD %
			2-10		8-25	31-68	38-96		18-48	CFD range
6	B + C	1.02	0	4e14	8e14	1.6e15	3e15	6e15	6e14	fluence (neq/cm^2)
			11	9	16	13	28	70	16	Optimal CFD %
			6-18	5-16	9-32	8-20	20-45	48-89	9-25	CFD range
8	B	1.02	0	4e14	8e14	1.6e15	3e15	6e15	6e14	fluence (neq/cm^2)
			8	23	15	44	68	75		Optimal CFD %
			3-12	9-37	9-26	23-60	28-83	48-96		CFD range
14	Ga	1.04	0	4e14	8e14	1.6e15	3e15	6e15	6e14	fluence (neq/cm^2)
			11	11	26	77	58		32	Optimal CFD %
			5-20	5-20	18-31	48-96	45-73		26-34	CFD range
15	Ga + C	1.04	0	4e14	8e14	1.6e15	3e15	6e15	6e14	fluence (neq/cm^2)
			12	10	20	32	54		23	Optimal CFD %
			6-19	6-28	14-30	23-42	48-70		12-34	CFD range

Table 2: Optimal CFD for several sensors and fluence. The CFD range is written as min-max CFD to have a 10% variation on the time resolution at the minimum.

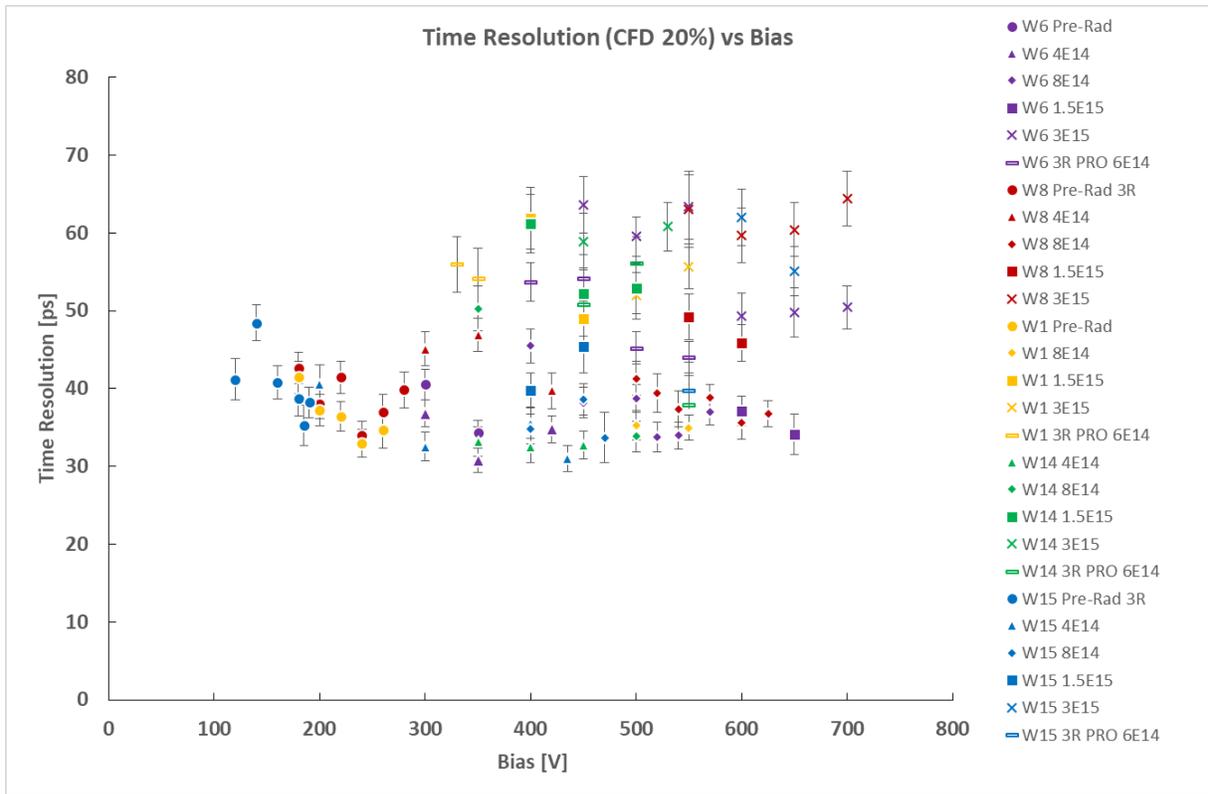


Fig 5: Time resolution as a function of bias voltage for all FBK sensors for a CFD threshold of 20 %.
W1 (Boron LD) W6 (Boron carbon) W8 (Boron) W14 (Gallium) W15 (Gallium carbon)

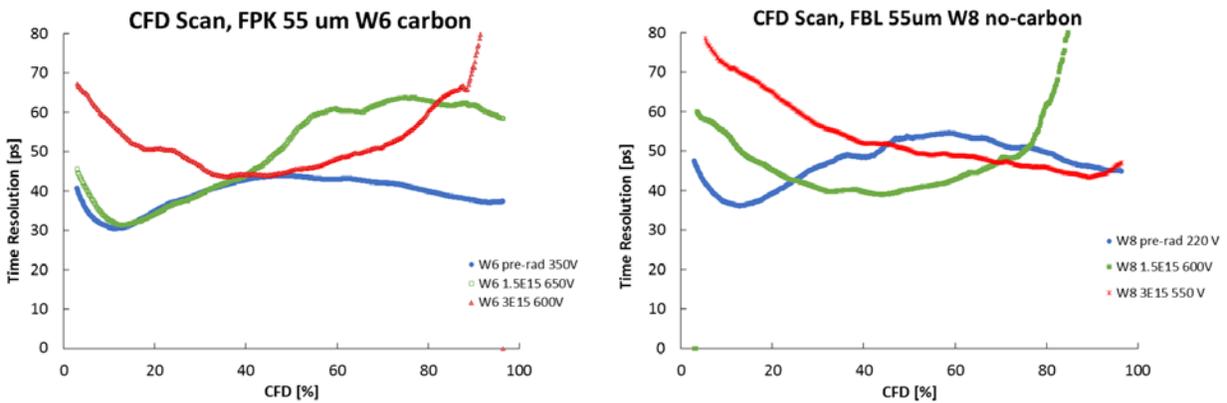


Fig 6: CFD scan at optimum operating voltage for FBK sensors W6 (Boron+Carbon) (left) and W8 (Boron) (right).

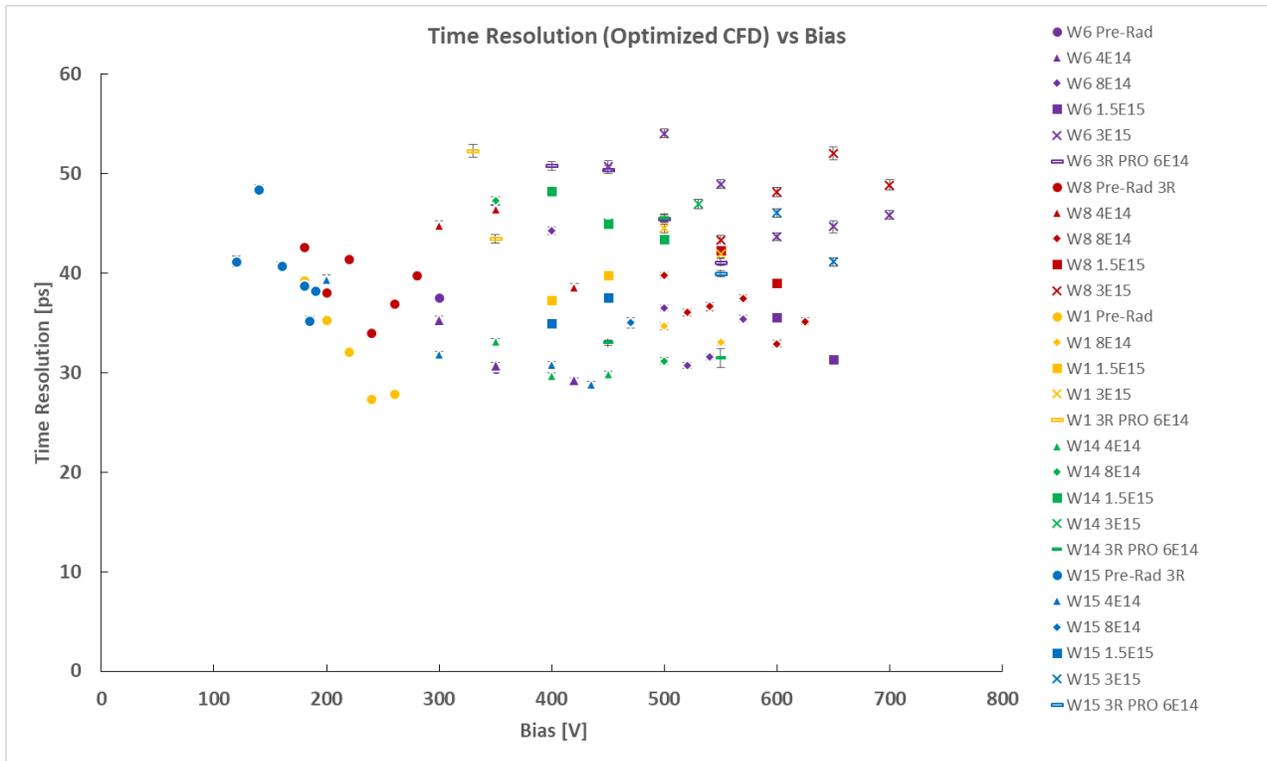


Fig 7: Time resolution as a function of bias voltage for a CFD threshold optimized for the optimal time resolution. W1 (Boron LD) W6 (Boron carbon) W8 (Boron) W14 (Gallium) W15 (Gallium carbon)

The CFD-optimized time resolutions as a function of fluence are presented in Fig. 8.

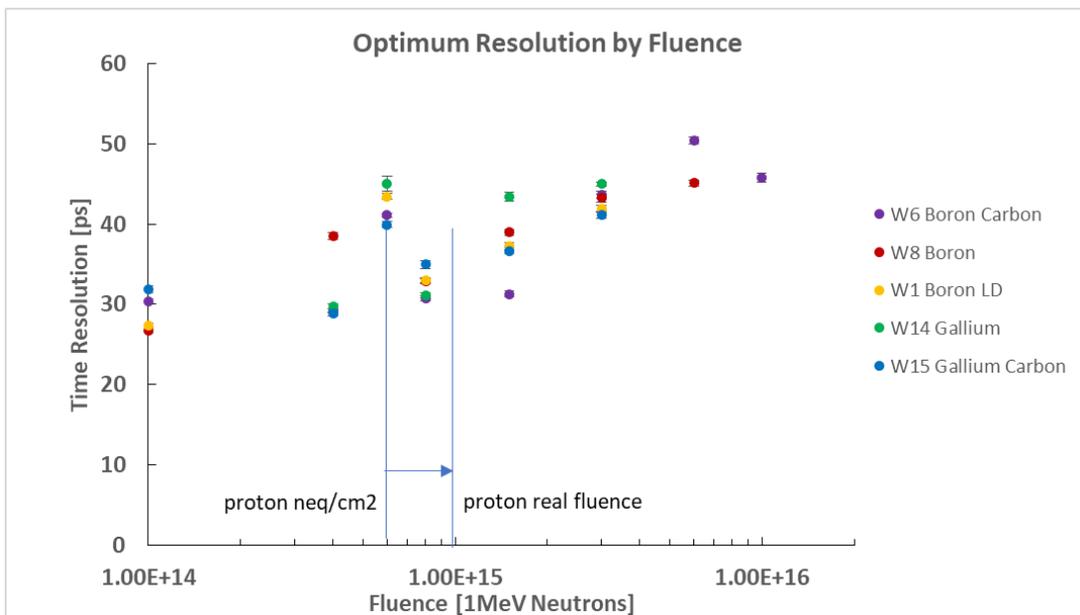


Fig 8: Time resolution as a function of fluence for FBK sensors. The proton data is in neq/cm² and it is indicated by a line in the plot, also the real proton fluence (9.4 p/cm²) is indicated. W1 (Boron LD) W6 (Boron carbon) W8 (Boron) W14 (Gallium) W15 (Gallium carbon) (The values before irradiation are shown at a fluence of 1E14 n/cm²)

6.4 Leakage current and noise

In Fig. 8 the leakage current is shown, before irradiation carbonated wafers (in particular W6) show higher current than non-carbonated wafers. However, after irradiation the leakage current is similar for all detectors. The noise is shown on Fig. 10, it is roughly constant around 1.5 mV with spikes from some of the detectors.

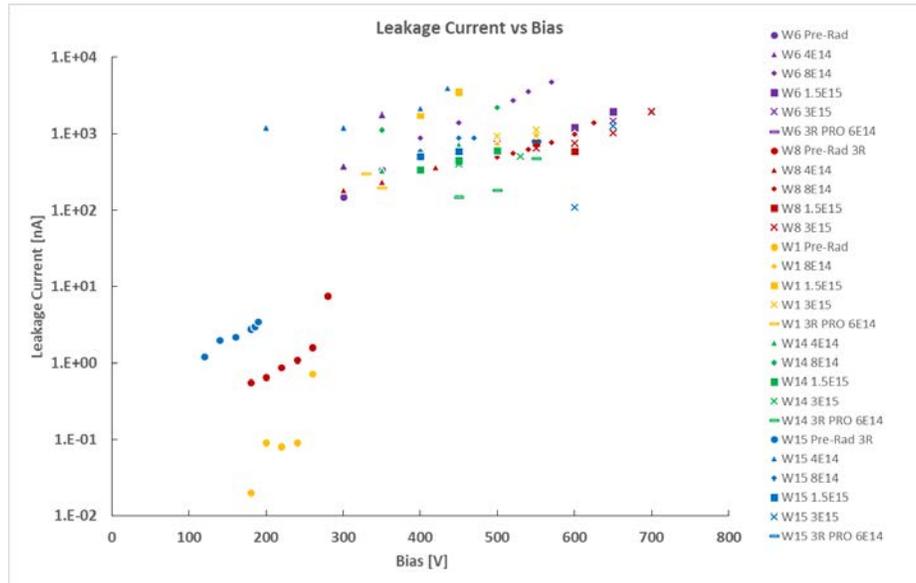


Fig 9: Leakage current for all FBK wafer before and after irradiation. Although W6 (Carbonated Boron) has a higher leakage current before irradiation it becomes similar to the other wafer after radiation damage.
W1 (Boron LD) W6 (Boron carbon) W8 (Boron) W14 (Gallium) W15 (Gallium carbon)

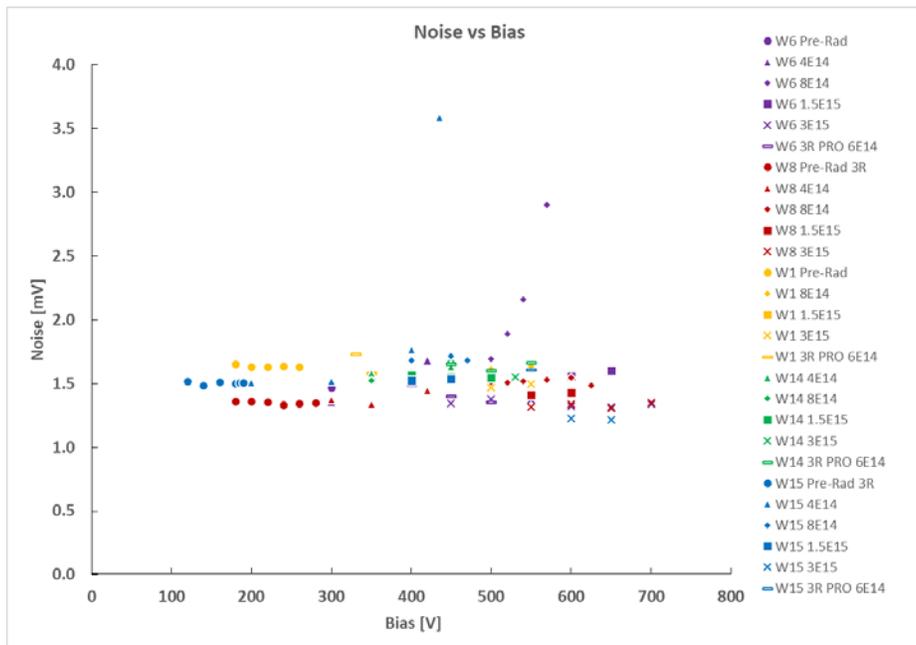


Fig 10: Noise on the oscilloscope for all FBK wafer.

7 - Conclusions

Several UFSD from Fondazione Bruno Kessler (FBK) of 60- μm thickness were tested using a ^{90}Sr β -telescope. The sensors were evaluated before and after neutron irradiation up to $3 \cdot 10^{15}$ n/cm² and for proton irradiation of $6 \cdot 10^{14}$ neq/cm². The operating voltage of the sensors ranges from 350 V (new) to 700 V ($3 \cdot 10^{15}$ n/cm² neutron irradiation).

All wafers have similar performance in terms of time resolution before irradiation. Post irradiation, carbonated boron sensors from wafer W6 (B+C) have equal or better time resolution and gain than the others using a fixed CFD of 20%. These results are in line with the preliminary studies done on the CV of the sensors in [20]. Some of the performance of the other type of sensors can be regained after irradiation by increasing the CFD threshold. Even with CFD optimization W6 maintains a CFD between 20 % and 35 % until $3 \cdot 10^{15}$ n/cm². Sensor with not carbonated boron (W1, W8) have similar performance to W6 sensor if the CFD threshold is increased up to 60% for $3 \cdot 10^{15}$ n/cm² of neutron fluence. Sensor with Gallium (W14, W15) doping instead show worse performance after irradiation, although Carbonated Gallium sensors (W15) are better than Gallium only sensors (W14).

The optimized time resolution of carbonated sensor is ~ 30 ps when new, this value is roughly maintained until $1.5 \cdot 10^{15}$ n/cm² of neutron radiation damage. For the higher fluence of $3 \cdot 10^{15}$ n/cm² ($1 \cdot 10^{16}$ n/cm²) the time resolution increases to ~ 45 (~ 50). The results from the proton irradiation will be reported in the future.

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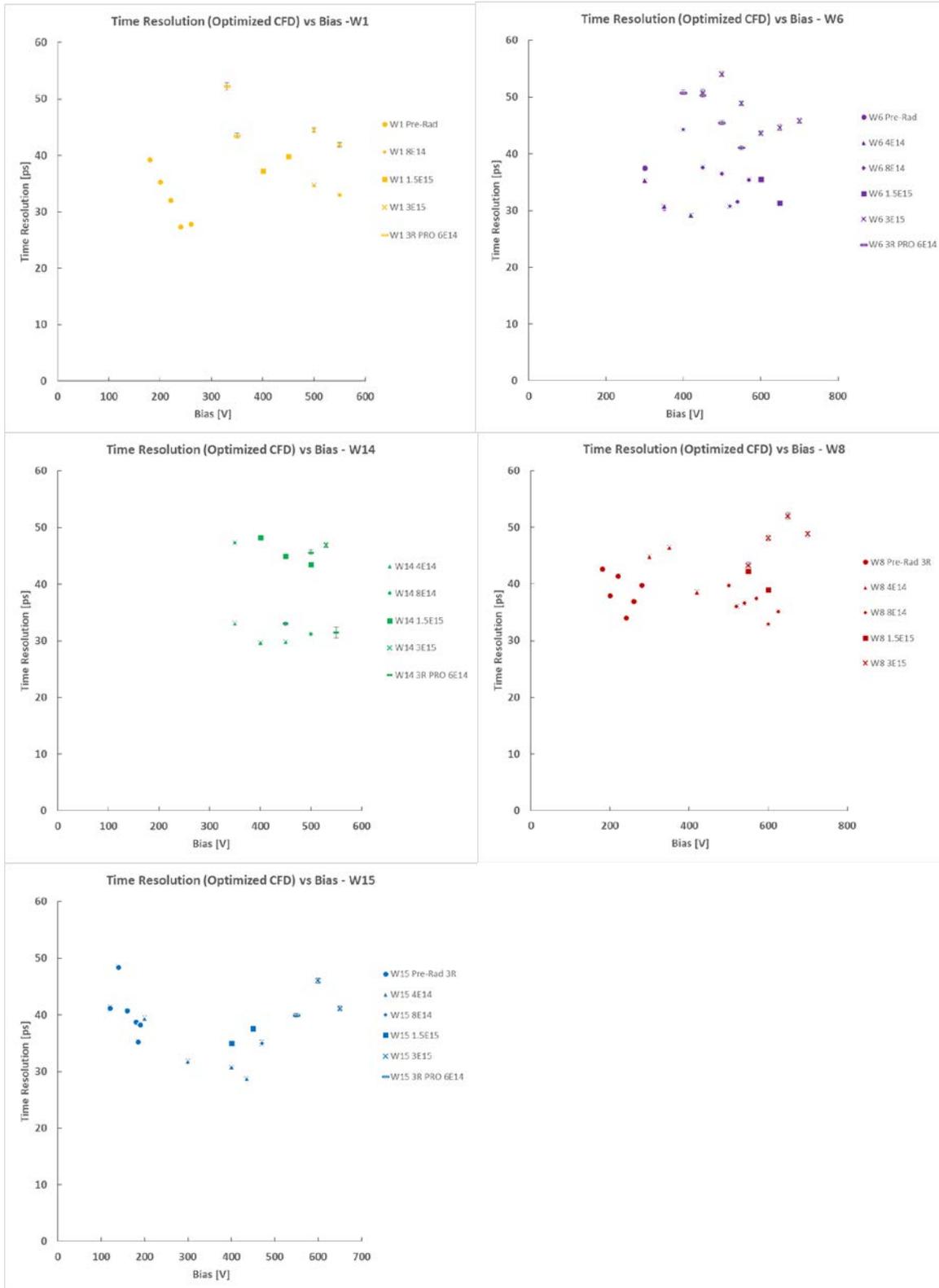
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Appendix A. – Time resolution vs bias voltage per sensor



Appendix B. – Time resolution vs bias voltage per sensor

