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# Thin LGADs as radiation-resilient sensors for 4D tracking

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Abstract: Precise tracking in space and time is becoming a more and more pivotal ingredient in designing high-energy physics experiments. Low-Gain Avalanche Diodes (LGADs) with an active thickness of $\sim 50\,\mu$m have proved the ability of silicon sensors to provide precise timing down to about 30 ps. At present, this timing performance is maintained almost unchanged up to a fluence of $2.5 \times 10^{15}\, n_{1\text{MeV eq.}}/\text{cm}^2$.

Thinner substrates can further improve the timing resolution and the radiation tolerance of the LGAD sensors.

At the end of 2022, FBK released a batch of thin LGAD sensors with an active thickness between 15 and 45 μm to investigate the effect of the thickness in improving sensor performances.

A new design of the sensor layout and periphery has been studied and manufactured, optimised for the sensor thickness and the requirement to withstand high electric fields up to very high fluences.

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The state-of-the-art design of the LGAD gain implant from FBK has been used on thin substrates, exploiting the concurrent implantation of boron and carbon atoms in the multiplication region typical of LGAD sensors. This resulted in the most radiation-tolerant LGADs ever produced by FBK.

The electrical characterisation of sensors before and after irradiation, together with the analysis of the signals from laser stimulus and charged particles, will be presented. The impact of the sensor thickness on the collected charge and the timing resolution will be explored and discussed.

Keywords: Materials for solid-state detectors; Radiation-hard detectors; Solid state detectors; Timing detectors

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## Contents



# 1 Introduction

Low-Gain Avalanche Diodes (LGADs) have become one of the main choices for timing sensors in high-energy physics experiments. The standard structure features an *n-in-p* design with a p-type bulk, a thin highly doped $p^+$ gain layer and a highly conductive $n^{++}$ electrode on top (figure 1) [1].

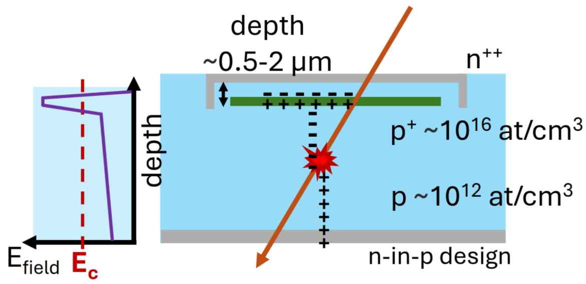


**Figure 1.** Structure of the n-in-p LGAD design used for the EXFLU1 production.

The locally high electric field ($E_C \sim 30\,V/\mu m$) generated by the gain layer triggers charge multiplication, with a controlled gain in the order of 20–30. The multiplication effect enhances the sensor signal amplitude while keeping low noise levels, enabling the use of thin LGADs (active thickness $\leq$ 55 µm) for precise timing measurements in hybrid detectors.

## 1.1 eXFlu project

The *eXFlu* project aims to improve knowledge and technological processes about high radiation-resistant silicon detectors, in order to enable 4D tracking for future high energy physics experiments up to very high fluences.

The first batch of this project, called EXFLU1, was manufactured at Fondazione Bruno Kessler (FBK) using an LGAD n-in-p design (figure 1) with different thicknesses for the active substrate (table 1). The FBK CBL[1] process for carbon-enriched gain layers has been used for all gain layer

[1] With the CBL process, both Carbon and Boron ions implanted in the gain layer are activated simultaneously through a low thermal diffusion.

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implantations, as it has previously been shown to be one of the best technologies in order to face radiation damages in the gain layer region [2].

**Table 1.** Specifications of the EXFLU1 batch of sensors with relative gain doping concentration and bulk type.

| Thickness (μm) | $p^+$ dose (a.u.) | Bulk resistivity |
|---|---|---|
| 45 | 1.14 | Very high $\rho$ |
| 30 | 1.12 | High $\rho$ |
| 20 | 0.96 | Low $\rho$ |
| 15 | 0.94 | Low $\rho$ |

The sensors have been tested before and after irradiation, performed at the TRIGA Mark II research nuclear reactor, operated by the Jozef Stefan Institute in Ljubljana. The sensors tested have been irradiated at different fluence levels, namely $\Phi = 8 \times 10^{14},\ 1.5 \times 10^{15},\ 2.5 \times 10^{15}\, n_{1\text{MeV eq.}}/\text{cm}^2$. After irradiation, the samples were annealed for 80 minutes at 60 °C.

### 1.2 Acceptor removal mechanism

Radiation damage carried out by charged particles in silicon detectors generates defects in crystal lattice throughout the different layers of the sensor. The main effects on the bulk are a reduction in charge collection efficiency due to the trapping of the charge carriers, an increase in the dark current level, distortion of the electric field profile, and an increase in the effective doping density. The effective doping density is related to the depletion voltage $V_{FD}$ of the sensor through the relation:

$$V_{FD} = e|N_{\text{eff}}|^2 \frac{d^2}{2\epsilon} \tag{1.1}$$

For this reason, irradiated sensors have to be operated at a higher reverse bias and require low temperatures to minimize the dark current.

Regarding the gain layer, radiation damage weakens the charge multiplication mechanism by transforming active dopant atoms into neutral defect complexes. This mechanism is called *acceptor removal* and has already been extensively studied for n-in-p LGADs [3]. The effective doping concentration in the gain layer is exponentially dependent on the irradiation fluence $\Phi$:

$$p^+(\Phi) = p^+(0)\, e^{-c_A \Phi} \tag{1.2}$$

The *acceptor removal coefficient* ($c_A$) decreases for higher values of the initial concentration $p^+(0)$, thus increasing the radiation resistance of the gain layer. This mechanism can still be mitigated by increasing the external reverse bias.

However, the bias level cannot exceed the *Single-Event Burnout* (SEB) limit. This phenomenon occurs for sensors exposed to high-energy particle beams while their bulk electric field is too high. The excessive amount of charge deposited within the sensor leads to a sudden and uncontrolled current flow, causing the silicon to melt along the path. The SEB limit has been proved to decrease with the sensor thickness, ranging from $E_{SEB} \simeq 15\, V/\mu m$ for 15 μm thick sensors to $E_{SEB} \simeq 11\, V/\mu m$ for 55 μm ones [4].



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## 2 Sensor characterisation

The sensors tested are single pads with small pixel pitch with two possible configurations: a single LGAD device ($1.3 \times 1.3\,\mathrm{mm}^2$) or an LGAD and a PiN sensor ($1 \times 1\,\mathrm{mm}^2$) on the same die (figure 2). The LGAD-PiN configuration is functional for the transient laser characterisation (section 2.2).

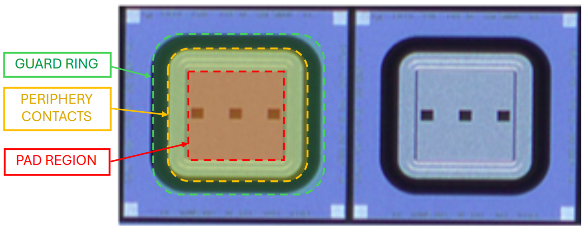
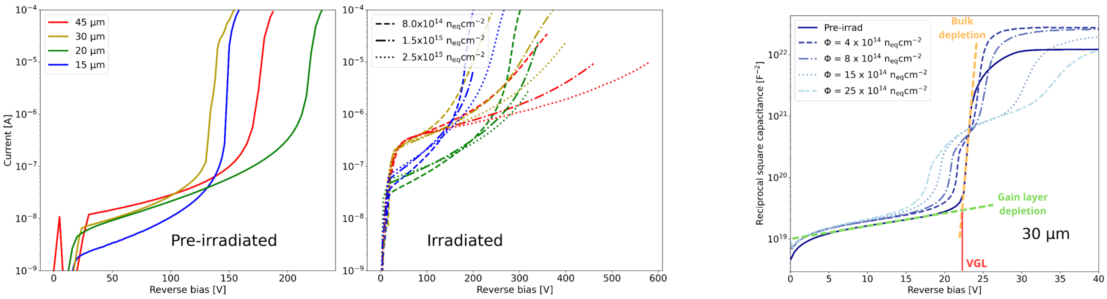



**Figure 2.** Example of an EXFLU1 Device-Under-Test (DUT) containing both an LGAD and a PiN sensor.

### 2.1 Electrical characterisation

All the samples have been tested before and after irradiation using an MPI TS200-SE probe station with a temperature-controlled chuck and needles for electrical connection with a Keysight B1505 power device analyser. Static measurements examine the current, $I$, and the capacitance, $C$, as a function of reverse bias, $V$, to evaluate the quality of the production while extracting precise values for gain depletion voltage, $V_{\mathrm{GL}}$, bulk depletion voltage, $V_{\mathrm{FD}}$, and breakdown voltage, $V_{\mathrm{BD}}$. $V_{\mathrm{BD}}$ is defined as the voltage reached by the sensor at the current compliance, set to 10 µA (figure 3(a)). $V_{\mathrm{GL}}$ is obtained through the intersection of a double linear fit approximating gain layer and bulk depletion respectively (figure 3(b)).




(a) I-V curve for $V_{\mathrm{BD}}$ evaluation (all thicknesses, all fluences).

(b) $1/C^2$ curve for $V_{\mathrm{GL}}$ extraction (30µm thickness, all fluences).

**Figure 3.** Static characterisation through I-V and C-V curves.

Given the direct correlation $V_{\mathrm{GL}} \propto p^{+}(\Phi)$ and the eq. (1.2), $V_{\mathrm{GL}}$ values are fitted against fluence in order to extract $c_A$ for each thickness (table 2). EXFLU1 $c_A$ values are finally compared to previous technologies [3], showing a noticeable improvement in radiation resistance (figure 4). The error bars are obtained as the RMSE of $c_A$ extracted for different samples from the same wafer.

**Table 2.** Acceptor removal coefficients for different thicknesses.

| Thickness (µm) | 45 | 30 | 20 | 15 |
|---|---|---|---|---|
| $c_A$ ($10^{-16}$ cm$^2$) | 1.36 | 1.34 | 1.37 | 1.37 |



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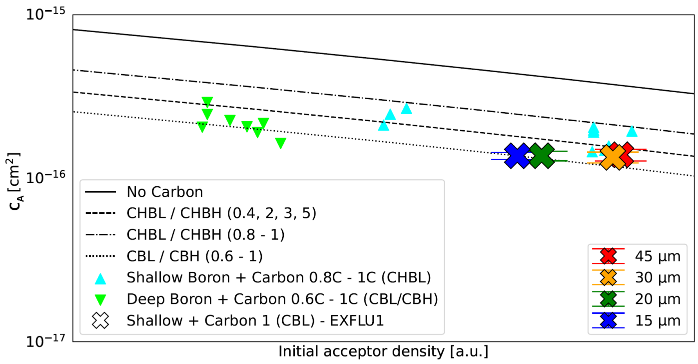


**Figure 4.** Acceptor removal coefficients measured for EXFLU1 sensors, compared to previous results [5]. Reprinted from [6], Copyright (2024), with permission from Elsevier.

## 2.2 Transient Current Technique

A transient characterisation has been performed to investigate the sensor signal when exposed to a stimulus. For this purpose, a Particulars Transient Current Technique (TCT) setup has been used, with a short-pulse infrared laser ($\lambda = 1064$ nm) focused on a 10 µm spot. All the measurements have been performed using a cooling plate set to $T \simeq -13$ °C and with the laser intensity calibrated to release in the sensor about 4 times the charge produced by a Minimum Ionising Particle (MIP). The gain of each sensor at a different bias point has been calculated as the ratio between the effective signal area $A_{\text{eff, LGAD}}$ for the LGAD divided by the average value of the effective signal area $A_{\text{eff, PiN}}$ in an analogous PiN[2] sensor implanted on the same die. Both values are measured by integrating the entire signal area and subtracting the baseline value.

$$G(V) = A_{\text{eff, LGAD}}(V)/\langle A_{\text{eff, PiN}} \rangle \tag{2.1}$$

In figure 5, the gain evaluated for different thicknesses is plotted as a function of the electric field increasing with the bias voltage. For irradiated sensors, the *SEB limits* are reported, representing the maximum electric field the bulk can withstand during operation on high-energy beams [4].

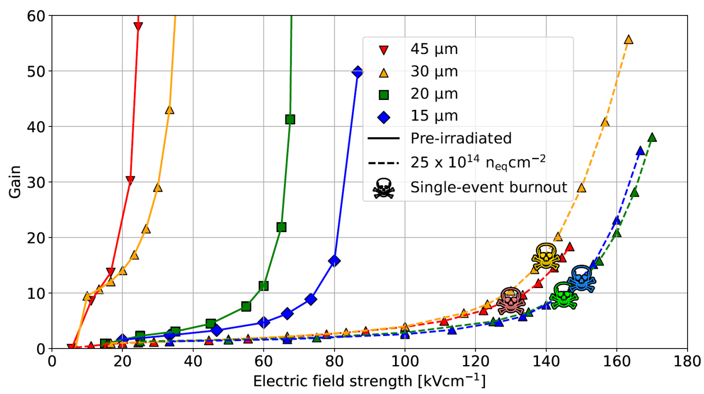


**Figure 5.** Gain evaluation for different EXFLU1 thicknesses, before irradiation and at the fluence of $2.5 \times 10^{15} n_{1\text{MeV eq.}}/\text{cm}^2$. Reprinted from [6], Copyright (2024), with permission from Elsevier.

[2]A sensor identical in design to the LGAD but without a gain implant, irradiated under the same fluence.

### 2.3 Timing performance

Timing resolution for non-irradiated sensors has been evaluated through tests with a $\beta$ source setup.[3] This setup features an MCP ($\sigma_t \simeq 8$ ps) as the trigger signal for the oscilloscope used during DAQ. All the measurements have been performed in a climate chamber at T = -25 °C.

The timing resolution has been evaluated as the standard deviation of the Gaussian obtained by fitting the overall distribution of all the time differences between the trigger and the DUT. The final timing resolution obtained for different thicknesses (figure 6) has proven to achieve very promising performance.

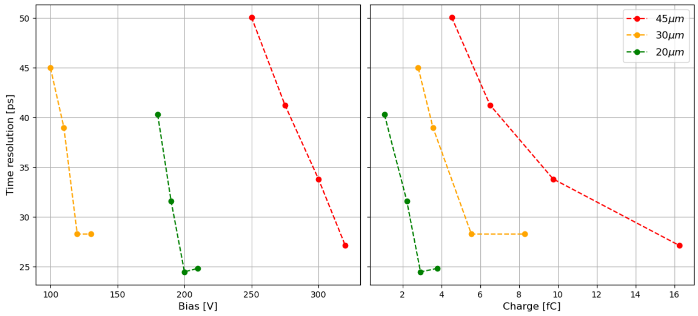


**Figure 6.** Timing resolution as a function of bias and collected charge, respectively, for different EXFLU1 thicknesses.

Further testing of thin sensors before and after irradiation will be performed through beam test measurements.

## 3 Conclusions

The EXFLU1 batch has given the possibility to deeply investigate the performance of thin LGADs for timing measurements in radiation-hard environments. The explored technology has proven to achieve very good performance regarding radiation hardness and timing resolution. Further testing will be performed on these sensors while investigating new technologies to achieve operation at higher fluences [7].

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[3] Sr90, maximum $e^-$ energy $E_\beta \simeq 2.2$ MeV.



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