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Characterization of the FBK-LGAD devices manufactured at an external foundry for large-volume productions

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Abstract: In recent years, the HEP detector community has shown an increasing interest in Low Gain Avalanche Diodes (LGADs) due to their excellent temporal resolution, good radiation resistance, and low material budget. An example of this is the upcoming CMS Endcap Timing Layer (ETL), a subdetector which will feature four disks (14 m^2) covered with these devices. In this context,

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Fondazione Bruno Kessler (FBK), one of the qualified producers of the ETL LGAD sensors, has recently initiated a technology transfer of the FBK-LGAD technology to an external CMOS foundry (LFoundry) in order to enable a larger and cost-effective production. The first prototype run from LFoundry was produced in May 2024. In order to evaluate the success of the technology transfer, this batch has been assessed against the CMS-ETL detector specifications. The initial characterization focused on the LGADs electrical properties (Leakage current, Breakdown Voltage, Depletion Voltage, Gain, Pad Isolation and Interpad distance). Additionally, a test beam at the H6 CERN hadron beam line allowed us to assess their performance in terms of collected charge and time resolution, while laboratory measurements on neutron-irradiated samples their radiation resistance. The positive results obtained are very promising for the future of large-scale LGAD production.

Keywords: Performance of High Energy Physics Detectors; Radiation damage to detector materials (solid state); Solid state detectors; Timing detectors

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Contents

1 Introduction

High Energy Physics (HEP) experiments are entering an era of unprecedented data rates, demanding precise time measurements in high-radiation environments. In this scenario, LGADs have established themselves as a cornerstone technology.

The LGAD technology is based on implanting a narrow p^+ layer, called Gain Layer (GL), close to the n^{++} electrode of an n-in-p silicon diode. This allows generate charge multiplication and creates fast-rising signals with a ~30–40 ps time resolution. Furthermore, radiation tolerance can be tuned via Gain Layer depth, dopant concentration, and carbon infusion [1].

Many future Time-of-Flight (ToF) detectors, including the CMS MIP Timing Detector (MTD), will require an LGAD coverage spanning tens of square meters. The MTD's Endcap Timing Layer (ETL) will, in fact, deploy LGAD devices over ~14 m^2 [2]. Meeting this scale requires the production of tens of thousands of sensors with uniform gain and high yield, driving the need for a scalable, industry-standard fabrication process.

In recent years, Fondazione Bruno Kessler (FBK) proved its ability to produce batches of 16×16 arrays of LGAD pads with a performance and uniformity the CMS requirements. This was assessed through many laboratory and beam tests [4] and lead to FBK's qualification as a possible supplier for the CMS ETL detector.

In 2024, FBK initiated a technology transfer (TT) of its LGAD production process to LFoundry, a CMOS foundry with proven experience in high-volume production. This TT aims to migrate FBK's sensor production from a 6″ wafer (the circular silicon discs used as the base substrate for LGAD fabrication) process to an 8″ flow, thereby doubling the exploitable area per wafer without proportional cost increases, while simultaneously validating industrial quality-control protocols and demonstrating consistent quality across multiple production runs. Underpinning this effort is the goal of establishing an industry-quality process capable of delivering large volumes of LGAD sensors (thousands of units) at a significantly reduced per-sensor cost.

2 The FBK-LFoundry production and the qualification plan

The first production of the collaboration between FBK and LFoundry consisted in fifteen 8″ wafers, each featuring 44 16×16 pad arrays and some smaller test structures (single pads and 1×2 pad arrays). The production is divided into wafers with two Gain Layer (GL) implantation depths: nine with a deep GL and six with a shallow GL. For both types, the GL featured carbon implantation to enhance radiation resistance. Additionally, the wafers were subjected to variations in the GL dopant dose.

The initial round of measurements on this production, performed 'on-wafer' (prior to dicing) directly at FBK during Q3 2024, focused on assessing the yield and uniformity of the first nine wafers (deep GL). As can be seen in table 1, the obtained results were promising, with yields consistently exceeding 90% and a good uniformity in gain response. Leakage currents were observed to be slightly higher than anticipated, but this was attributed to defects in the substrate material rather than to issues in the implant process.

Table 1. Sensor yield of the first 9 wafers of the FBK-LFoundry production.

Wafer	# Good sensors	# Bad sensors	Yield
1	36	8	81.8%
2	41	3	93.2%
3	39	5	88.6%
4	43	1	97.7%
5	40	4	90.9%
6	43	1	97.7%
7	41	3	93.2%
8	42	2	95.5%
9	42	2	95.5%

Following this evaluation, the sensors were diced and shipped to the University of Turin. There, a full characterization campaign was launched on W1 and W2 samples (identical deeo GL wafers) to verify their compliance with CMS-ETL LGAD specifications [3].

As standard, this campaign encompassed performance tests on unirradiated sensors (measurement of the collected charge, time resolution, leakage current), post-irradiation measurements at multiple fluences (charge, timing, acceptor removal coefficient), and interpad characterization.

3 Performance evaluation of the unirradiated samples

3.1 Collected charge and time resolution at a beam test

The first step of the FBK-LFoundry devices evaluation took place at the CERN SPS H6 beamline (PPE156 area). There, 4 single-pad devices were characterized with a 120 GeV hadron beam (mainly π and κ). Each one of these sensors was attached to a Santa-Cruz (SC) board [5]; the boards were then installed in a cold box, maintained at a constant temperature of 15 °C.

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Instead of an external trigger, a logical AND of the signals from all four sensors was used. The LGAD signals passed through a second amplification stage, a 20 dB CiviDec amplifier, were recorded on an 8-channel Teledyne-Lecroy HDO9404 oscilloscope, and then analyzed offline. The described configuration allowed to calculate, at various bias voltages, the collected charge and the time resolution of the Devices Under Test (DUTs) [1].

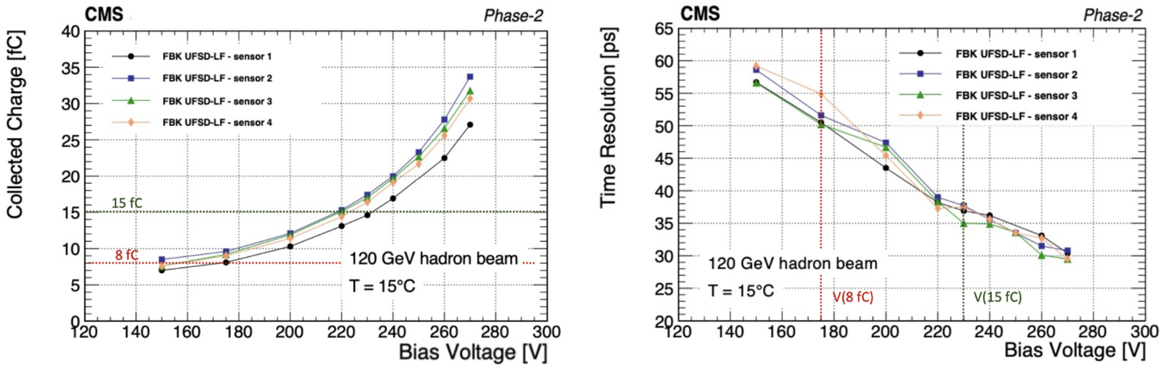

Figure 1. Results of the FBK-LFoundry W1 single pad LGADs evaluation. Left: collected charge against Bias voltage. Right: time resolution against Bias voltage.

Figure 1 (left) shows the collected charge versus bias voltage trends of the DUTs: the devices exhibit an uniform behavior and they all exceed 8 fC at 175 V and 15 fC at 230 V. The bias voltages at which the collected charge reaches these predetermined thresholds, denoted as V(8 fC) and V(15 fC), are significant as the CMS requirements for the ETL LGADs timing performance are specified in terms of them. Since the experimental setup for this measurement campaign lacked of a timing reference, the time resolution σ_t was extracted computing the Δ_t between the four devices.

The CMS-required time resolution for ETL LGADs is $\sigma_t < 70$ ps at V(8 fC) and $\sigma_t < 50$ ps at V(15 fC). As illustrated on the right-hand side of figure 1, the four DUTs not only exhibited a high degree of homogeneity but also achieved timing resolutions well below the CMS limits. Measured values ranged from 55 to 60 ps at V(8 fC) and from 35 to 40 ps at V(15 fC).

3.2 Evaluation of the 16×16 devices leakage current with a probe card

The FBK-LFoundry samples were next characterized at Turin's Laboratory for Innovative Silicon Sensors (LISS) via I–V scans (measure of the leakage current as a function of bias voltage) on nine W2 16×16 LGAD arrays. Each sensor was placed on the metal chuck of a probe station [1] and contacted on its top surface with a 258-needle probe card (256 for the pads, 2 to ground the LGAD guard-ring), enabling its leakage-current measurement per pad.

The probe card was interfaced to a Keysight B1505 Power Device Analyzer through a mezzanine board. The chosen mezzanine board short-circuited all 256 pads into a single output to evaluate the device's total leakage current.

The measurement was performed at 20 °C by increasing the bias with 2 V steps until the current reached 300 µA. From these I–V scans (figure 2, left) two key parameters can be extracted. The first is the leakage current at V(8 fC) for which the CMS requirement is to remain below 10 µA. Since these measurements were done at 20 °C, determining V(8 fC) requires applying a +5 V shift relative to the value obtained during the beam-test characterization at 15 °C (~1 V/ °C). The second

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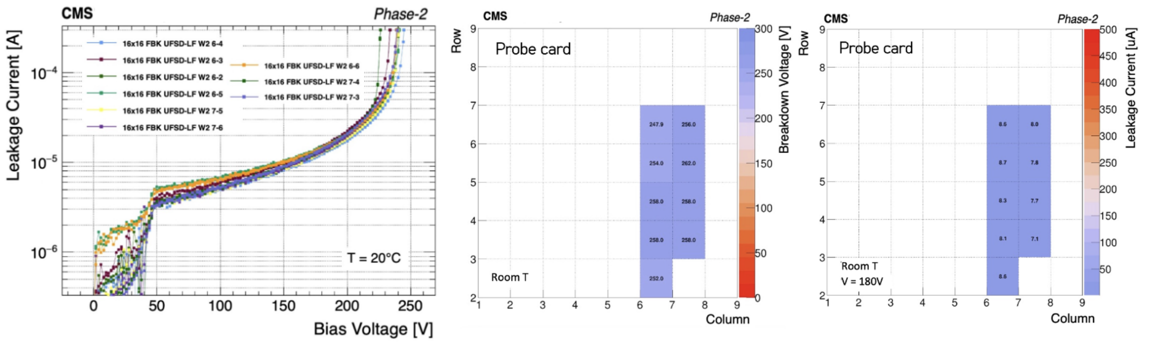

Figure 2. Results of the FBK-LFoundry W2 I-V scans on the 16×16 LGAD arrays. Left: I-V trends of the 9 W2 tested samples. Centre: value of breakdown voltage of each sample. Right: value of I_{leakage} at 180 V.

important parameter is the breakdown voltage (V_{BD}), defined as the bias voltage above which the k-factor (k = $(\Delta I/\Delta V)\cdot(V/I)$) exceeds 20. CMS requires for V_{BD} to be in the range 130–280 V.

The plots on the right of figure 2 show that the FBK-LFoundry production met both CMS thresholds with a V_{BD} in the range 245–270 V and I_{Leakage} at V(8 fC) between 7 µA and 9 µA. Although this leakage remains below the limit, its proximity to the threshold was taken into account in the overall assessment of the production performance.

4 Performance evaluation of the irradiated samples

An important aspect of an LGAD production characterization is verifying post-irradiation performance. To this end, twenty 1×2 W1 LGAD arrays were neutron-irradiated: half of them at a fluence of $1{\cdot}10^{15}$ n_{eq}/cm^2 (low fluence) and the others at $1.5{\cdot}10^{15}$ n_{eq}/cm^2 (high fluence). Each device underwent I–V scans at -25 °C; the extracted breakdown voltages were $V_{\mathrm{BD}}(1e15) > 500$ V and $V_{\mathrm{BD}}(1.5e15) > 700$ V.

4.1 Measurement of collected charge and time resolution using a beta setup

Two irradiated samples (one per fluence) were evaluated for collected charge and time resolution in the beta setup at Turin's LISS. The DUTs, glued and wire-bonded to SC boards, alongside a Photonis microchannel-plate photomultiplier (MCP), used both as a trigger and as a time reference (σ_t = 15 ps), and a ^{90}Sr β-source were placed in a 3D-printed telescope inside a climate chamber held at -25 °C. After a second stage amplification done with 20 dB CiviDec amplifiers, the LGAD were signals recorded on a 4-channel Teledyne-LeCroy HDO9404 oscilloscope, and analyzed offline to extract collected charge and time resolution at various bias voltages.

Figure 3 presents the obtained results alongside an unirradiated reference curve measured at the beam test (shifted by -40 V due to ΔT). The low fluence sample exceeded 8 fC at 400 V, whereas the high fluence device required 550 V to collect this charge. At V(8 fC), time resolutions of 37 ps (low fluence) and 38 ps (high fluence) were recorded. Both measurements are well within the CMS benchmark of 50 ps, demonstrating that the devices maintain excellent timing performance even after significant radiation exposure.

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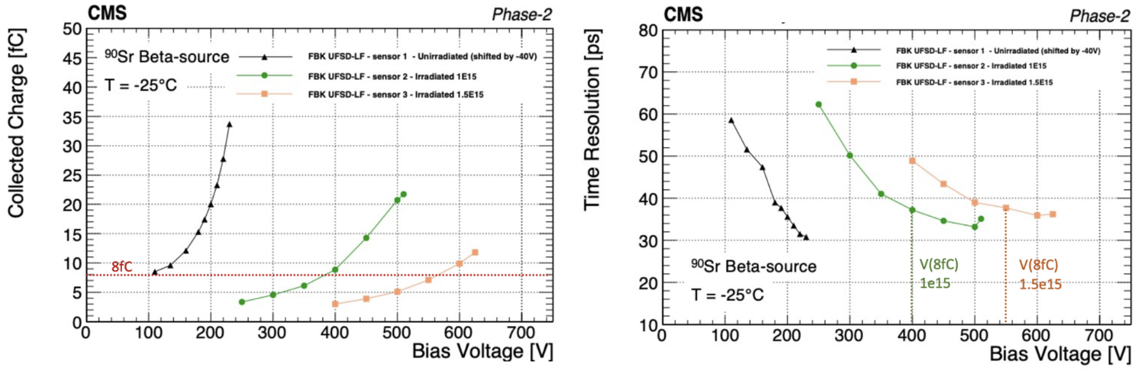

Figure 3. Results of the FBK-LFoundry W1 1×2 irradiated LGADs evaluation. Left: collected charge against Bias voltage. Right: time resolution against Bias voltage.

4.2 Determination of the acceptor removal coefficient

To complete the radiation-resistance evaluation, the acceptor removal coefficient c_a was calculated, which quantifies gain-layer preservation after irradiation (Fraction of gain implant = $e^{-c_a \cdot \Phi}$, where ϕ is the received fluence).

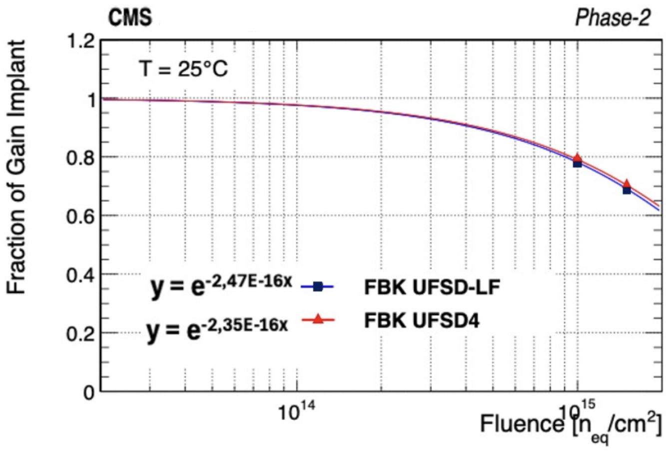

Figure 4. Fraction of Gain implant against received fluence comparison between FBK-UFSD4 and FBK-LFoundry productions.

c_a was extracted through capacitance vs bias scans on fifteen 1×1 FBK-LFoundry W1 devices: five unirradiated, five irradiated at $1{\cdot}10^{15}$ n_{eq}/cm^2 and five at $1.5{\cdot}10^{15}$ n_{eq}/cm^2. From these scans it was obtained the average Gain Layer depletion voltage V_{GL} for each irradiation group [1]. The gain implant fraction at a fluence ϕ was the computed as the ratio $V_{GL}(\phi)/V_{GL}(\phi{=}0)$.

An exponential fit to these values yielded $c_a = 2.47 \cdot 10^{-16}$, which was then compared to the FBK-UFSD4 W17–18 one ($c_a = 2.35 \cdot 10^{-16}$), a previous production from FBK entirely executed in FBK foundries, that demonstrated to meet CMS radiation-resistance requirements. As shown in figure 4, both productions exhibit compatible values, indicating robust radiation tolerance of the new FBK-LFoundry production.

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5 Interpad measurements

To conclude the analysis, the interpad region (i.e., the no-gain area region between two pads of an LGAD array) of this production had to be characterized.

First, the interpad width d_{ip} of an unirradiated W1 1×2 device was measured using a 1 kHz pulsed laser (λ = 1064 nm, 8 µm spot size). The laser was scanned across two pads while recording the number of detected signals at each position. On the resulting histogram (figure 4, left), two S-curve fits were applied, and d_{ip} was defined as the distance between the full widths at half maximum (FWHM) of the fits. The measured value was 72.5 µm, well below the 90 µm requirement.

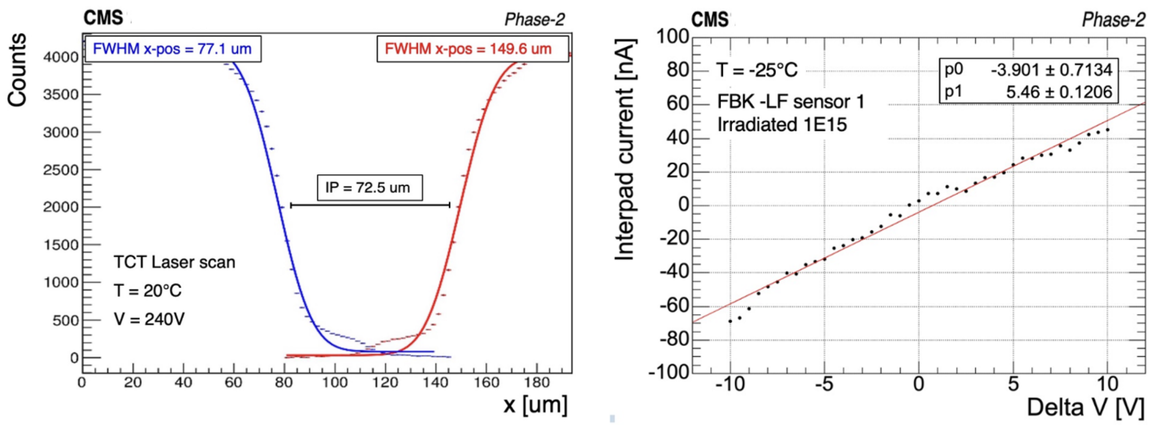

Figure 5. Interpad characterization of the FBK-LFoundry production. Left: measurement of the interpad distance on a 1×2 array. Right: example of interpad resistance evaluation.

Secondly, it was evaluated the electrical isolation between adjacent pads by measuring the interpad resistance R_{ip}. CMS requires an $R_{ip} > 0.1 \cdot 10^6\,\Omega$ for both unirradiated and irradiated sensors. The R_{ip} evaluation was carried out at the LISS in Torino using a probe station set at a temperature of -25 °C. In this experimental setup each DUT, all 1×2 LGAD structures, was brought to a fixed bias voltage (V_{BD} - 80 V); a ΔV, between -10 V and +10 V with a 0.5 V step, was then applied between the two pads of the array. At each step the interpad current I_{ip} was recorded.

Since I_{ip} is linearly dependent by ΔV, with coefficient $1/R_{ip}$, the interpad resistance was extracted through a linear fit on $I_{IP}(\Delta V)$ plot (as shown in figure 5, right). For three 1×2 structures with different irradiation levels, it was found that: the unirradiated sample has $R_{ip} = 2.85 \cdot 10^{12}\,\Omega$, the one irradiated at a low fluence has $R_{ip} = 0.18 \cdot 10^6\,\Omega$ and the one irradiated at a high fluence features $R_{ip} = 0.14 \cdot 10^6\,\Omega$. All measured values satisfied the CMS requirement, confirming the absence of cross-talk between neighboring pads.

6 Conclusions

A comprehensive characterization campaign was carried out on both unirradiated and irradiated samples from the FBK–LFoundry LGAD production (W1–W2), following the CMS ETL qualification protocol. All key performance parameters met the required specifications, confirming the overall quality of the production. The only exception was the leakage current, which approached the upper specification limit. This issue was traced back to the choice of substrate material. Despite this, the technology transfer from FBK to LFoundry has proven successful, demonstrating the feasibility of large-scale LGAD production while preserving sensor performance.

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