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Technology developments and first measurements of Low Gain Avalanche Detectors (LGAD) for high energy physics applications

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ABSTRACT

This paper introduces a new concept of silicon radiation detector with intrinsic multiplication of the charge, called Low Gain Avalanche Detector (LGAD). These new devices are based on the standard Avalanche Photo Diodes (APD) normally used for optical and X-ray detection applications. The main differences to standard APD detectors are the low gain requested to detect high energy charged particles, and the possibility to have fine segmentation pitches: this allows fabrication of microstrip or pixel devices which do not suffer from the limitations normally found [1] in avalanche detectors. In addition, a moderate multiplication value will allow the fabrication of thinner devices with the same output signal of standard thick substrates.

The investigation of these detectors provides important indications on the ability of such modified electrode geometry to control and optimize the charge multiplication effect, in order to fully recover the collection efficiency of heavily irradiated silicon detectors, at reasonable bias voltage, compatible with the voltage feed limitation of the CERN High Luminosity Large Hadron Collider (HL-LHC) experiments [2]. For instance, the inner most pixel detector layers of the ATLAS tracker will be exposed to fluences up to 2×10^{16} 1 MeV n_{eq}/cm^2, while for the inner strip detector region fluences of 1×10^{15} n_{eq}/cm^2 are expected.

The gain implemented in the non-irradiated devices must retain some effect also after irradiation, with a higher multiplication factor with respect to standard structures, in order to be used in harsh environments such those expected at collider experiments.

1. Introduction

All avalanche diode detectors [3] have a region with a high electrical field so as to cause multiplication of signal charges (electron and/or holes) that transverse the region. The gain mechanism is achieved within the semiconductor material by raising the electric field as high as necessary to enable the migrating electrons to create secondary ionization during the collection process [1]. Normally, the junction is made up of a thin highly doped n-type layer on top of a moderately doped p-layer in which multiplication (of electrons) takes place. The substrate can be a p^- high resistivity silicon wafer that can be operated in fully depletion mode, if required.

The amplification mechanism is normally provided by avalanche multiplication [4]. In very high electric fields (> 200 kV/cm) charge carriers may acquire enough energy to create an electron–hole pair, a process called 'impact ionization'. The newly generated charge carriers can themselves create more pairs, initializing a multiplication chain which leads to detectable signals. Because of their lower mobility, holes are less likely to create electron–hole pairs and therefore it is simpler to fabricate devices that multiply only electrons.

The standard approach [5] followed by the HEP community in developing new radiation hard silicon detectors has been to investigate the radiation effect in detectors using the simplified geometry of a single pad detector, i.e., a single pad n+/p/p+ structure with a guard ring. In a second step, selected radiation damage studies on prototype HL-LHC detectors modules have been carried out to evaluate the new technology and the degree of degradation of microstrip or pixel devices after irradiation, simulating the overall years of operation.

For this reason, in this paper we are presenting new avalanche pad detectors with low gain (LGAD) fabricated with a technology based on APD but with a modified doping profile, in order to have detectors suitable to be used for tracking in high energy physics

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experiments (such as colliders) and resistant to the high radiation fluencies expected in the future LHC upgrade at CERN [2]. If a significant improvement of the collected charge is found after heavy irradiation, this geometry can be directly applied to micro-strip and pixels sensors.

The idea proposed here is to fabricate p-type pad detectors with a small gain, already shown in their pre-irradiation responses. We expect that the gain implemented in the non-irradiated devices could retain some effect also after irradiation with a higher multiplication factor with respect to standard structures. The moderate multiplication value will allow the fabrication of thinner devices with the same output signal of standard thick substrates. The signal gain should be limited to avoid crosstalk and to prevent the signal from exceeding the dynamic range of readout electronics. The low gain also results [6] in reductions of detector noise, as well as in increased stability at a given gain with respect to changes in applied bias, device temperature, or impurity concentration of local fluctuations.

Besides, the gain should have a weak dependence on temperature and bias voltage (after full depletion) changes.

A Sentaurus TCAD simulation was performed to predict the electrical behavior of the proposed structures since some of the new technological solutions might compromise the voltage breakdown properties. The capacitance behavior of these new devices is to be studied too, since an increase of the capacitance value will increase the noise, worsening the signal to noise ratio, even for the highest gain values.

By studying LGAD it is also possible to better understand the multiplication mechanism and investigate directly a method for boosting the charge collection of planar devices after irradiations. Charge multiplication effects in irradiated devices have been also studied within the RD50 CERN community [7,8] and diodes have shown the largest multiplication factors after neutron and proton irradiations [9], presumably due to the uniformity of the field.

In this paper we show the first electrical measurements and charge collection studies obtained with MIP particles before and after irradiations with neutrons at fluences up to 2×10^{15} 1 MeV - n_{eq}/cm^2.

2. Technology and simulation

The first LGAD diode detectors were fabricated at CNM-IMB [10] clean room facilities by diffusing a p-type layer just below the n+ electrode, as shown in Fig. 1. Thus, an $n^+/p/p^-$ junction is created along the center of the electrodes. Under reverse bias conditions, a high electric field region is generated in this localized region, which can lead to a multiplication mechanism for the electrons reaching the n^+ electrode. The objective of the p layer is to enhance the value of the electric field in that region, and its impurity profile will be the main technological parameter to define in order to adjust the gain value. The premature breakdown of this quite narrow n+/p junction should be prevented by the wider n+ electrode diffusion.

A previous analysis and design optimization of the LGAD main parameters was performed using Sentaurus TCAD simulation toolkit in order to assure the gain values required in tracking experiments before and after irradiations. A detailed model used for the simulation of these devices can be found in [11].

Simulations show that the adjustment of the impurity profile in this region is critical, due to its effect on the gain and on the voltage capability for the detector under study. The p-well dose must be high enough to obtain a determined gain without a reduction of the breakdown voltage. As shown in Fig. 2, small modifications in the boron implant dose (on the order of 2×10^{12} cm^{-2}) can induce huge changes on the gain and breakdown voltage values. Therefore, the accurate control of the doping profile in the multiplication area is the most important technological condition for the fabrication of LGAD.

Gain uniformity throughout the whole detection area is desired in order to ensure the same multiplication on the signal wherever the charge is collected. Thus, the electric field distribution should be engineered to approach the typical distribution of a planar junction. A simple edge termination structure for the multiplication junction, based on widening the n+ electrode beyond the p-well mask dimensions (as represented in Fig. 1), shows a high field peak at the edge, visible in the plot in Fig. 3. This may introduce certain non-uniformity in the gain distribution.

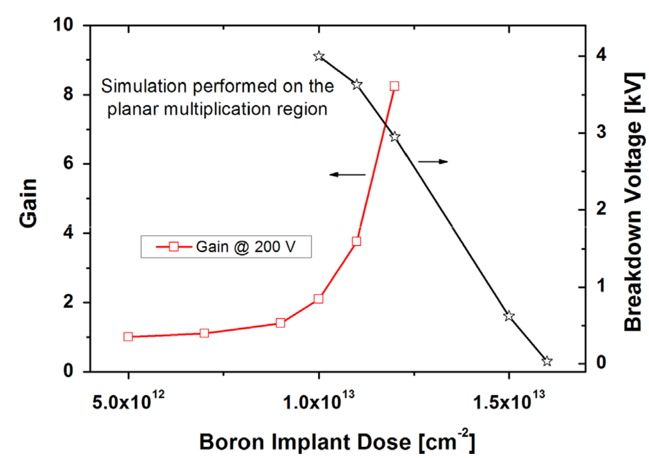

Fig. 2. Simulated dependence of gain and breakdown voltage as a function of the boron dose implanted to form the p well.

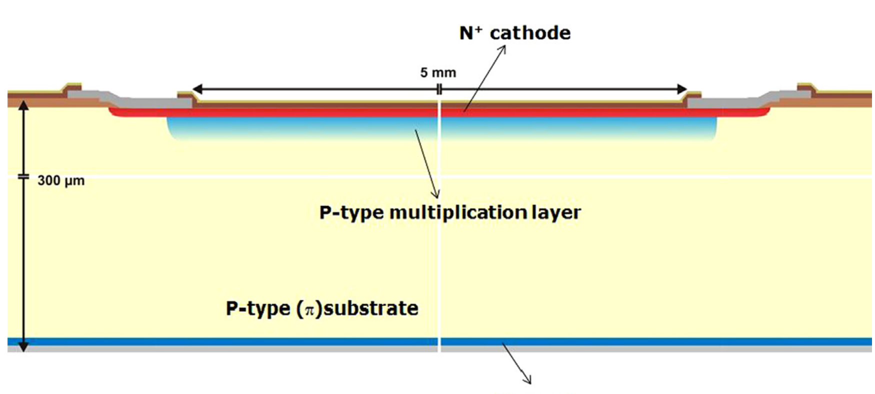

Fig. 1. Schematic cross-section of the LGAD pad design. A p-type layer is diffused below the n^+ electrode to form the $n^+/p/p^-$ junction where the multiplication takes place.

An alternative junction termination extension (JTE) design has been proposed (see Fig. 4) for the LGAD detectors fabricated so far. The JTE consists of overlapping the main junction edge with an n-type diffusion of lower doping concentration, which extends deeper than the n+ electrode diffusion. In Fig. 5 the electric field distribution in a junction ended with a JTE is represented. It shows a better uniformity, very similar to the one typical of a planar junction. In addition, the voltage capability of the devices is significantly increased to a 95% of the value expected for a planar junction [12]. The electric field peak at the junction edge is reduced below the critical value to trigger impact ionization, avoiding multiplication at the edge termination even for the highest voltage bias. As shown in Fig. 3, the peak height can be further reduced if the JTE edge is protected with a field plate extension of the electrode metal.

3. Electrical characterization

LGAD prototypes (diodes with an area of 5×5 mm^2 and without guard ring) were characterized at the CNM-IMB facilities in order to evaluate their electrical response under typical operational conditions. The measurements were performed individually on all the samples, when on wafer and after dicing, in a controlled temperature (20 °C) and humidity environment. Cathode current and bulk capacitance values were measured as a function of the reverse applied bias, which was swept up to the power supply limit (1100 V). LGADs from wafers implanted with a target boron dose of 1.6×10^{13} cm^{-2} have shown large voltage capability, without reaching breakdown condition throughout the covered voltage range. Devices with higher implant dose of 2×10^{13} cm^{-2}, for which higher gain values are expected, have shown lower breakdown voltage values (around 800 V). The implant doses used for the fabrication are higher than the values predicted by simulation (as shown in Fig. 2). The experimental tests have shown that the target implant dose of 1.3×10^{13} cm^{-2} is not able to produce avalanche multiplication. In the same way, breakdown voltage remains still high up to doses over 2×10^{13} cm^{-2}. Hence, a shift with respect to the simulated value is observed. Anyhow, simulation predictions are still valid in a qualitative way, although they should be refined by the experimental measurements.

Standard PiN diodes fabricated following the same process as the LGAD, but without the multiplication layer, showed voltage capabilities above 1100 V as well. An overview of the characteristics of a sample of devices extracted from the same wafer (with boron implant dose $= 1.6 \times 10^{13}$ cm^{-2}) is given in Fig. 6. Although all devices exhibit high voltage capabilities up to 1100 V, the current levels can be grouped in three different ranges: (1) below 1 μA; (2) between 1 and 10 μA; (3) over 10 μA. First insights into the technological process history suggest that the current dispersion may be originated by a non-uniform distribution of the p-well doping concentration throughout the wafer. PiN samples do not show current spread and their current values remain always below 1 μA, with a high degree of uniformity throughout the wafer. This fact corroborates the suggested hypothesis, since the p-well structure is not implemented for PiN diodes.

Bulk capacitance was measured, as well, as a function of the applied bias. Fig. 7 shows the $1/C^2$–V curve for LGAD samples from

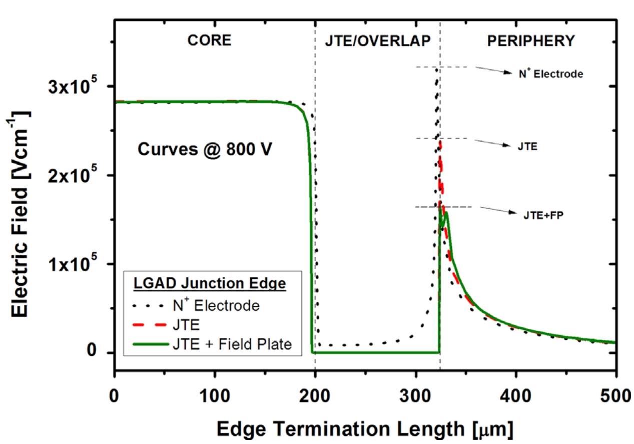

Fig. 3. Simulated electric field distribution at the multiplication junction edge for different termination designs: n$^+$ electrode extension, JTE, and JTE with field plate.

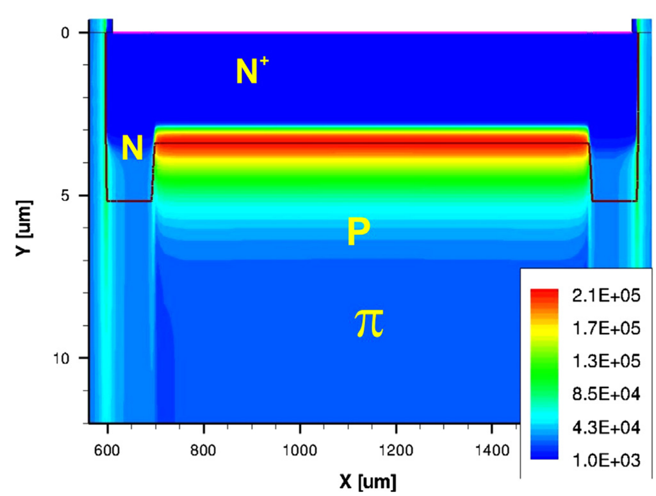

Fig. 5. Simulated electric field distribution throughout the multiplication junction of a LGAD ended with a JTE.

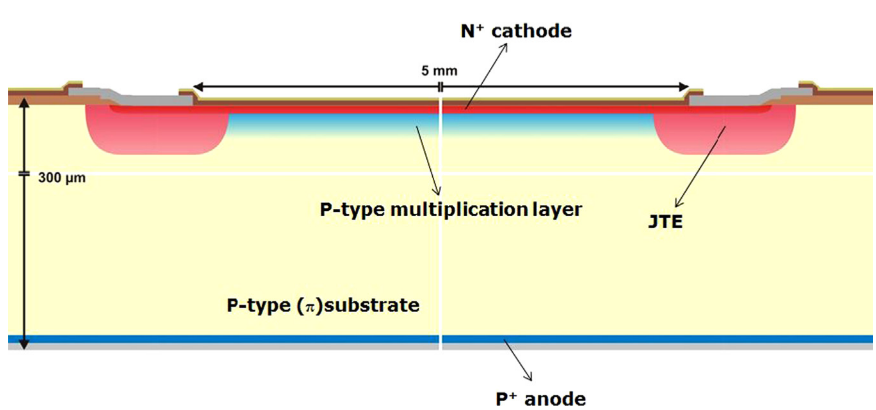

Fig. 4. Schematic cross-section of the LGAD pad design with a JTE structure protecting the junction edge termination.

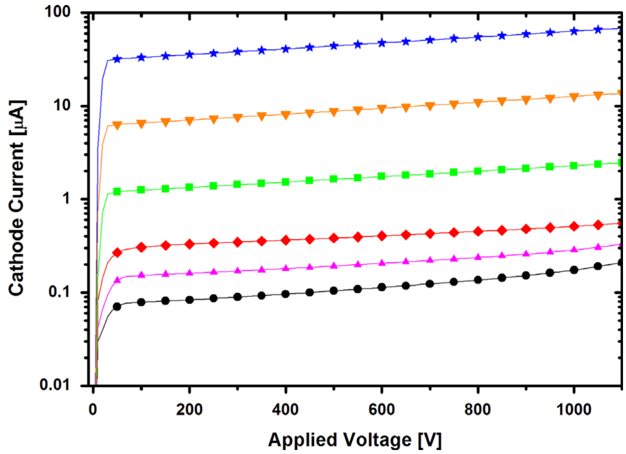

Fig. 6. I–V curves for a sampling of the fabricated device. Each curve corresponds to similar samples located on the same wafer with boron implant dose $= 1.6 \times 10^{13}$ cm^{-2}, can be grouped in three ranges, according to their current levels: $I < 1$ μA; 1 μA $< I < 10$ μA; and $I > 10$ μA. Voltage capability beyond 1100 V has been shown in all cases.

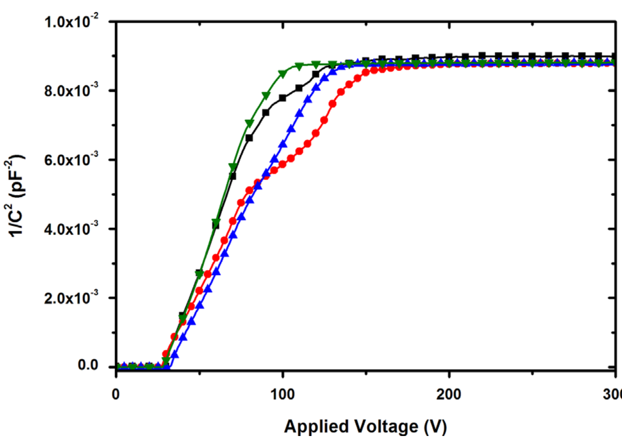

Fig. 7. $1/C^2$–V curves for a sampling of the fabricated devices. Each curve corresponds to similar samples located on the same wafer with boron implant dose $= 1.6 \times 10^{13}$ cm^{-2}.

the same wafer and with boron implant dose equal to 1.6×10^{13} cm^{-2}. The capacitance value barely varies for the lowest applied voltage values (< 30 V), while the p-well depletes. Then, the space-charge region exhibits a fast advance through the lowly doped substrate until the depletion edge reaches the p$^+$ electrode. From this point on, the capacitance holds its value slightly above 10 pF for all measured devices. The full depletion voltage can be extracted from the plot as the value at the intersection of the two linear trends represented in the graphic. All measured devices show full depletion values between 70 V and 100 V. However, some devices show a hump in the curve before this condition is achieved. Although further study is required to reach an ultimate conclusion, the anomalous tendency of the capacitance may be also related to the non-uniform distribution of the p-well boron concentration within the fabricated devices.

4. Charge collection measurements

Charge collection performances of the LGAD prototypes were evaluated at the JSI facilities in Ljubljana (Slovenia). Non-irradiated samples were exposed to a Sr-90 source, and the signal response was processed with a LHC-type electronic setup [13]. Fig. 8 depicts the absolute charge collection as well as the noise signal of two

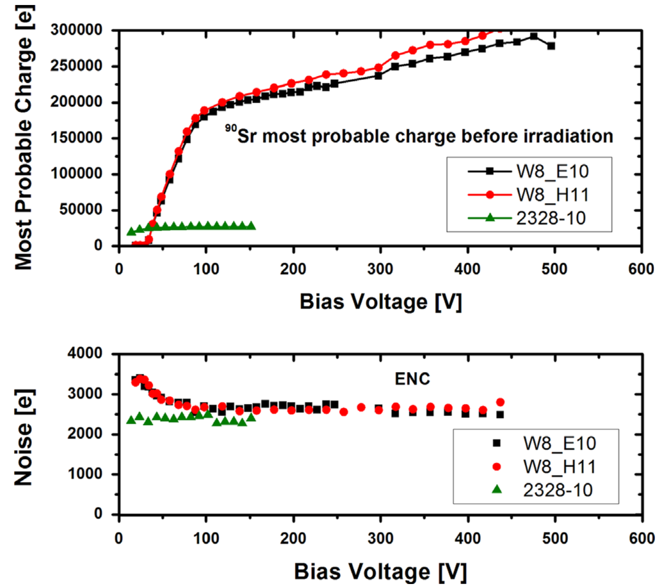

Fig. 8. Absolute collected charge (up) and noise (bottom) signals for two LGAD samples after Sr-90 source MIPs exposure. Measurements are compared with the response of a conventional non-multiplying pad diode (2328-10).

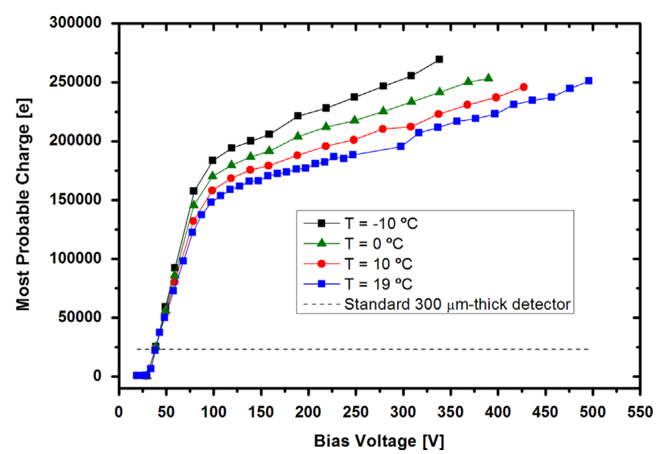

Fig. 9. Temperature dependence of the multiplication factor. Charge collection response for a MIP has been measured at different operational temperatures. The expected signal for a standard 300 μm-thick detector has been depicted with a dashed line to allow the comparison with a non-multiplying detector.

LGAD samples, and of a conventional pad detector (2328-10). The LGAD signals exhibit an improvement of a factor 8 at 300 V compared to the signal given by the PiN-type detector. The signal amplification contrasts with the absence of multiplication in the noise signal, which remains at the levels of the pad diode for both LGAD samples.

The temperature dependence of the multiplication factor has been examined too. Fig. 9 shows the absolute charge collected for Sr-90 MIPs at different temperatures. Multiplication experiences an increase as the temperature is reduced, moving from a factor 8 at 300 V for room temperature to a factor 10 for -10 °C. The gain seems to be limited to a factor around 10, as the breakdown condition is reached above this value. Indeed, the breakdown voltage decreases at the lower temperatures. Both effects were expected, since the impact ionization coefficients exhibit temperature dependence, becoming larger as the temperature is reduced [14].

Finally, LGAD samples were irradiated at different neutron fluences to emulate the accumulated damage expected for detectors during their operation. As shown in Fig. 10, the multiplication

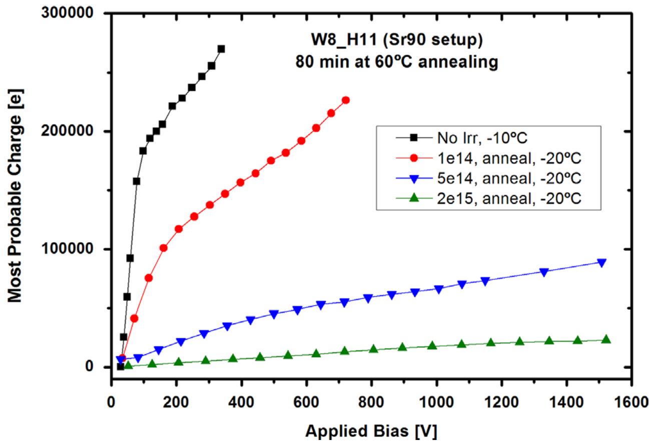

Fig. 10. Measured absolute collected charge as a function of the applied bias for a LGAD sample irradiated to different fluences.

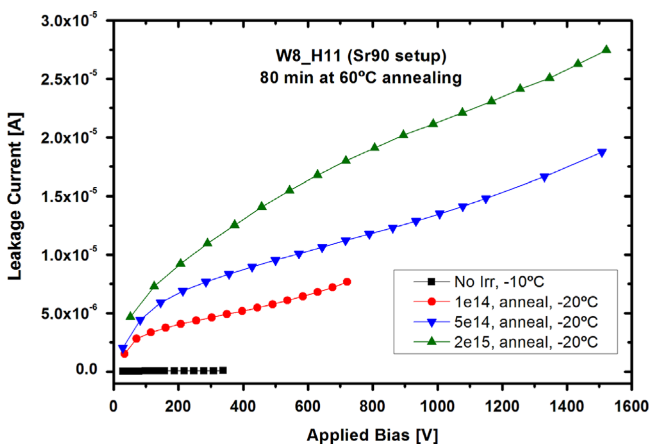

Fig. 11. Measured leakage current as a function of the applied bias for a LGAD sample irradiated to different fluences.

factor decreases significantly with fluence. This effect is not predicted by simulation anyway the irradiation is known to partially remove the implanted acceptors of the p^+ section at the junction. The p^+ concentration is affected (reduced) by irradiation and the high electric field achieved with this production technology is diminished.

The measurements were performed on the same device after subjecting it to progressively increasing neutron fluences. Before each measurement, the sample underwent 80 min annealing at 60 °C.

Although the breakdown performance is good, the leakage current exhibits a large increase as the irradiation fluence becomes higher (see Fig. 11). Irradiation damage introduced within the substrate tends to reduce the substrate resistivity, thus increasing the leakage current. In non-multiplying detectors the current is expected to increase linearly with fluence. However, LGAD measurements represented in Fig. 11 show a smaller increase as a consequence of the counteracting effect of the multiplication degradation.

5. Conclusions

The first LGAD diode detectors have been fabricated and they have shown excellent breakdown performances before and after irradiations. Simulation shows that the adjustment of the p+ implant is critical, due to its effect on the gain and on the voltage capability for the detector studied.

LGAD detectors exhibit a signal improvement of a factor 8 at 300 V compared to the signal given by the PiN-type detector. The multiplication factor experiences an increase as the temperature is reduced, moving from a factor 8 at 300 V for room temperature to a factor 10 at −10 °C.

The multiplication factor decreases significantly for detectors irradiated with neutrons, anyway staying above 1 for fluences up to 2×10^{15} 1 MeV n_{eq}/cm^2.

The preliminary results reported in this paper show that LGAD detectors technology can be considered as an option for the detectors of the HL-LHC experiment. Anyway further studies are still required in order to prove that this technology can be applied to segmented detectors (pixel and strips) and that their radiation hardness will withstand the fluences expected in the innermost layers of the experiments, up to 2×10^{16} 1 MeV n_{eq}/cm^2.

Acknowledgments

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