Low Gain Avalanche Detectors for High Energy Physics

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***Abstract*—This paper describes a new concept of Silicon radiation detector with internal multiplication of the charge generated by the incident particle, known as Low Gain Avalanche Detector (LGAD), with a gain in the range of 10-20. The LGAD is addressed to tracking applications for high energy physics with enhanced performances compared to the conventional detectors based on the PiN diode structure. The physical behavior, the critical design challenges and the first experimental data on the fabricated LGAD prototypes is described in the paper.**

Keywords—Avalanche Photodiode, Radiation Detectors, LGAD, PiN Diode, Tracking

I. INTRODUCTION

Radiation detectors fabricated using the well stablished Silicon technology, are largely employed in high energy physics as particle trackers [1] and are based on the PiN diode structure. The detection of a particle is achieved by reverse biasing the PiN diode at a high enough voltage value to produce a wide depletion region but not that high to cause avalanche breakdown. Therefore, the incident particle generates an amount of electron-hole pairs which is, in the linear region, proportional to its energy. Depending on the starting low doped substrate used to implement the PiN diode, electrons or holes will travel through the reversed junction with a high electric field value towards the electrode. Conventional PiN diodes offer good efficiency, quite large energy spectrum detection (due to the low Silicon band gap) and can be implemented using pad, strip or pixel layout. However, Silicon PiN diodes are seriously affected by thermal (increase of the leakage current) and electronic noise. Moreover, the exposition of Silicon PiN diodes to high irradiation fluence causes a fast degradation of the signal-to-noise ratio and irrecoverable radiation damage (effective substrate doping increase and subsequent leakage current increase [2]).

The performance of the conventional PiN detectors is enhanced when an internal gain is used to multiply the amount of charge reaching the readout electronics. Therefore, the signal-to-noise ratio is strongly increased and the thermal and electronic noise effects are minimized. In this sense, the Avalanche Photodetectors (APD) [3], commonly used in optoelectronic and X-Ray [4] detection applications, offer a much higher gain with two possible operating modes (linear and Giger). However, there is a noise associated to the multiplication process which can adversely modify the signal-to-noise ratio. Indeed, the detection current levels inherent to APDs are too high to be compatible with the standard readout electronics used in high energy physics experiments (CERN).

Low Gain Avalanche Detectors (LGAD) [5] represent a remarkable advance in high energy particle detection, since they provide a moderate multiplication (gain ~20) on the collected charge, thus leading to a notable improvement of the signal to noise ratio, which largely extends the possibilities of application of silicon detectors beyond their present working field. This work summarizes the design and optimization aspects of the LGAD detectors fabricated at the IMB-CNM clean room, as well as the main results of the characterization tests performed in several laboratories and institutions assigned to the CERN RD50 collaboration [6].

II. LOW GAIN AVALANCHE DETECTORS

The cross section of an LGAD detector, based on the standard PiN diode, is shown in Fig. 1. The $P^+/\pi/P/N^+$ structure of the LGAD includes a moderately doped P-type diffusion beneath the N-type electrode, which allows the generated charges to undergo avalanche multiplication before being collected. In this sense, the LGAD operating mode is analogous to that of the APDs with a lower gain value on the output signal (~20, against 100-1000, or even higher, for an APD counterpart), which makes LGAD more suitable for the detection of high energy charged particles. In contrast with the APDs, detected signals are moderately increased in LGADs, without significant increase of the noise levels, thus improving the signal-to-noise ratio of the detector. In addition, LGAD detectors offer the possibility to have fine segmentation pitches, thus allowing the fabrication of micro-strip and pixel devices, which do not suffer from cross-talk in their readouts.

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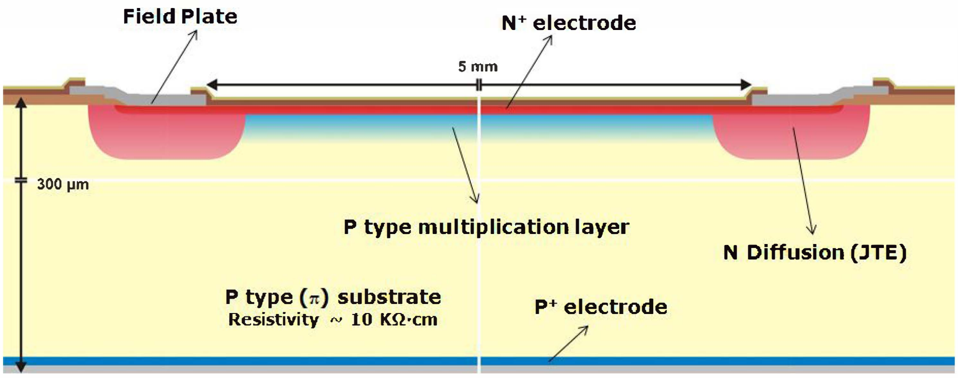

Fig. 1. Schematic cross section of the LGAD core region, with the P/N+ multiplication junction properly protected with a deep N-type diffusion, which overlaps the junction edges, preventing premature breakdown of the junction.

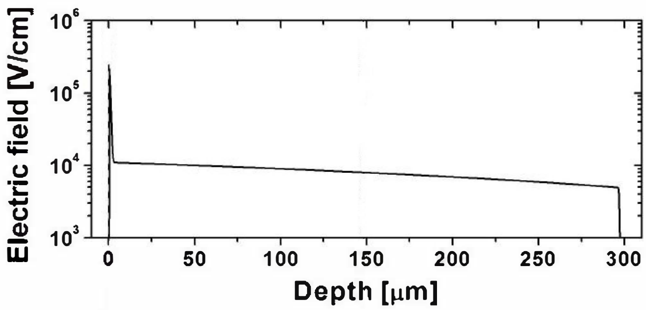

Fig. 2 Simulated electric field distribution at a reverse bias of 400 V within the core region of an LGAD detector.

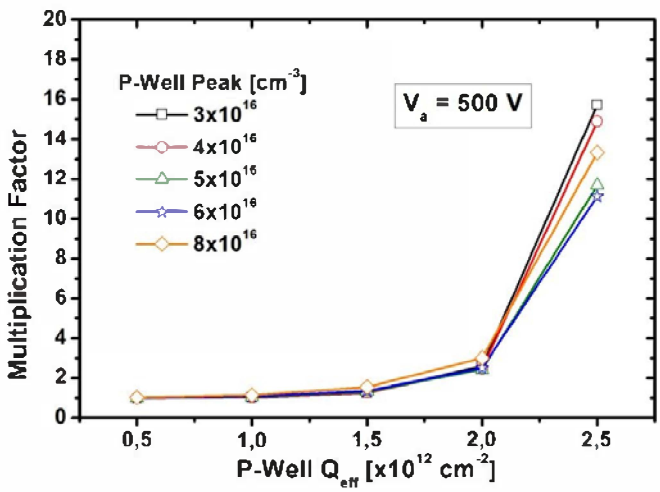

Fig. 3 Simulated trade-off optimization between gain and voltage capability as a function of the implanted Boron dose.

The LGAD core region, where the multiplication takes place, is provided with a proper edge termination design, consisting of a deep N-type diffusion, which overlaps the lateral curvature of the multiplication junction, preventing a premature cylindrical breakdown, as well as ensuring the stability and uniformity of the electric field distribution across the whole junction area. The simulated electric field profile plotted in Fig. 2 clearly shows an electric field peak in the N^+P junction in the range of 2×10^5 V/cm, close to the critical electric field value which would lead to avalanche breakdown. The deep JTE diffusions are implemented as a typical Junction Termination Extension (JTE) edge termination technique, commonly used in power semiconductor devices. However, in the LGAD case, the edge termination efficiency is not measured in terms of the percentage of the theoretical maximum breakdown voltage achieved but in terms of focalization of the maximum electric field peak at the core junction.

The additional narrow P layer enhances the electric field in the core region but may lead to a premature breakdown if the doping concentration is too high (Zener breakdown). Therefore, the definition of this P layer is the key step of the process technology and a deep TCAD simulation analysis has been carried out to optimize the trade-off between the gain and the voltage capability of the core region. The implanted Boron dose has to be high enough to ensure a gain in the range of 10-20, as plotted in Fig. 3, but no too high due to the voltage capability degradation as a consequence of the slower depletion of the added P-multiplication layer. If the integrated charge in this layer is high enough, the substrate is no longer depleted and the device resembles a Zener diode. Therefore, small manufacturing fluctuations of the implanted dose can induce huge changes in the gain and voltage capability.

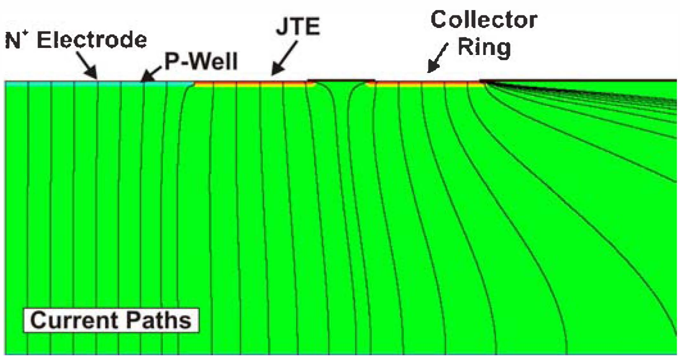

Fig. 4 Simulated current paths on an LGAD structure including a collector ring to split the bulk and the surface current readout.

The peripheral region, between the JTE edge termination and the channel stopper located in the scriber line, includes different strategies to avoid the collection of the surface leakage current component. This current is normally considered as a noise source, since it is not generated by the incident particles. Indeed, the surface of the extremely high resistivity P-type substrate, used to achieve full depletion at a voltage lower than 100 V, can be easily inverted if a sufficiently high charge concentration is found in the field oxide. As a consequence, a collector biased N-type ring confines the sensitive volume of the detector to the core region, since most of the charge carriers generated outside are extracted separately by the ring. In this sense, the current path simulation shown in Fig. 4 clearly proves the effectiveness of the additional ring in collecting the peripheral current.

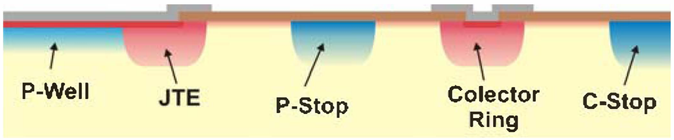

Fig. 5 Schematic cross section of the LGAD peripheral region including P-Stop, Channel-Stop, collector ring and shallow P-Spray diffusion placed to prevent the formation of a surface inversion channel.

Although the additional ring strongly reduces the total leakage current, two more diffusions are also implemented in the peripheral LGAD region to avoid the undesirable effects derived from the surface inversion of the extremely low resistivity substrate as a consequence of the positive fixed charges of the field oxide. Once the surface n-channel is created, there is a direct path for the electrons towards the collector ring and the JTE diffusion, thus masking the degrading the LGAD signal-to-noise ratio. The P-Spray shallow diffusion is a blanket low dose and low energy Boron implantation performed at the beginning of the fabrication process through a thin thermal oxide to prevent from surface inversion. However, the control of the final doping profile of the P-Spray is not easy due to the large number of thermal steps and the los dose used. Hence, an additional deep P-Stop diffusion with a maximum doping concentration in the range of 10^{18} cm^{-3} is implemented to cut any possible surface current path for the electrons. Finally, the P-Stop diffusion is also used to create a Channel-Stop diffusion to prevent the depleted region to reach the edge of the LGAD die with the subsequent increase of the leakage current due to the defects created by the dicing process.

III. PROTOTYPE PERFORMANCE

LGAD prototypes with a pad layout (detection area of 5x5 mm²) where fabricated at the IMB-CNM Clean Room on 300 µm P-type substrates and subjected to various characterization tests in different laboratories of the CERN RD50 collaboration. The evaluation of the charge collection efficiency with a β-particle ^{90}Sr source was carried out at the JSI facilities in Ljubljana (Slovenia). Non-irradiated samples were exposed to the β-particle source and the detected signal was processed with a LHC-type electronic setup [7]. The charge collection results plotted in Fig. 6 corresponds to the absolute charge collection (up) and to the noise signal measured on two LGAD samples and on a commercial PiN detector (2328-10). The LGAD signals are 8 times higher than that of the PiN diode at 300 V. Indeed, the noise remains at the level of the PiN diode in both LGAD samples.

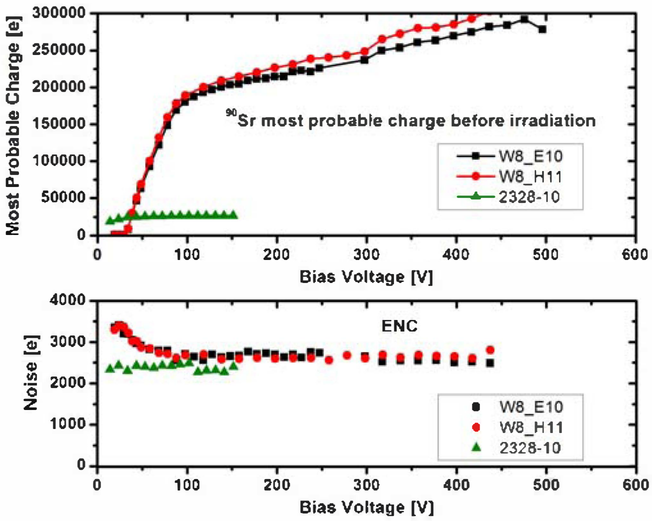

Fig. 6 Most probable value of the collected charge (up) and Eiquivalent Noise Charge (ENC) (down) measured in two LGAD samples exposed to a β-particle ^{90}Sr source, compared with the signals of a commercial PiN diode.

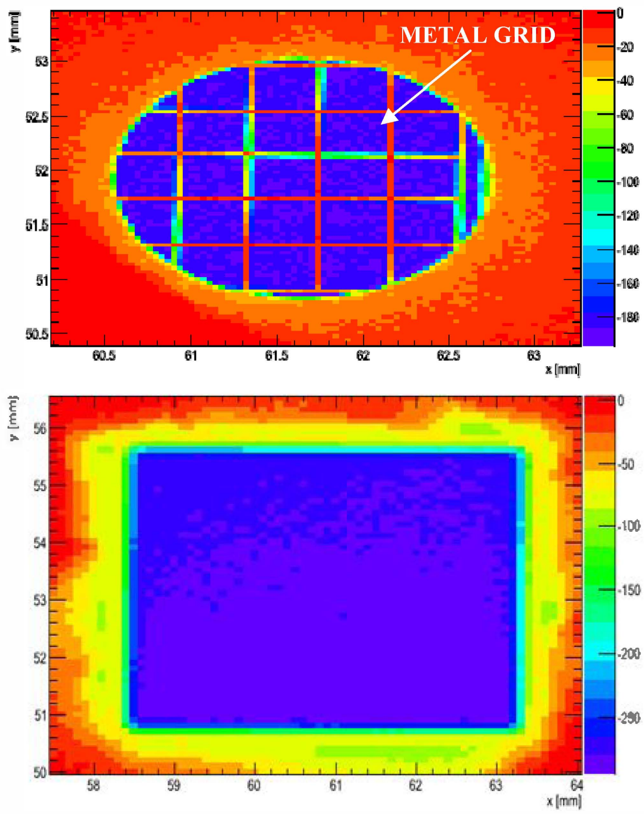

Fig. 7 Charge collection and multiplication uniformity evaluated on a LGAD sample using the TCT technique applied with a red laser in 100 µm steps to cover the whole detection area. Back side (top) and fron side (bottom).

The Transient Current Technique (TCT) was also applied to LGAD samples at CERN and IFCA-CSIC (Santander) facilities. A red laser and an α-particle source was used to scan from front and back sides with 100 and 75 µm steps, respectively. The TCT images shown in Fig. 7 demonstrate that the multiplication process within the junction area is really uniform in both sides of the die.

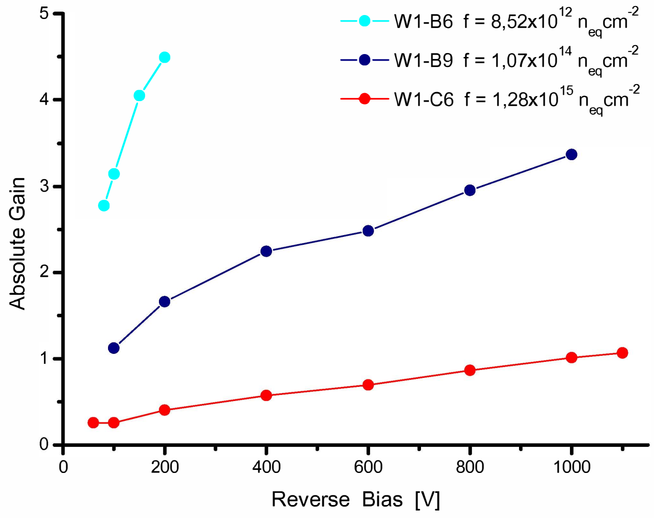

Fig. 8 Reduction of the absolute gain in a LGAD prototype submitted to different proton irradiation fluences, as a consequence of the multiplication process degradation. Proton fluences are given in equivalent neutron fluence.

LGAD samples were irradiated to different proton and neutron fluences to determine the accumulated damage during their expected normal operating conditions in a detector environment. Neutron irradiation at fluences up to 1×10^{16} cm^{-2} with 80 min anneal at 80ºC demonstrated that the gain is reduced to almost 1. LGAD detectors have also been irradiated with 800 MeV protons with no additional anneal. Results of proton irradiation reported in Fig. 8 also show a dramatic reduction of the absolute gain at high fluences. This effect was not initially predicted by TCAD simulations although it is well known that tha irradiation partially removes the implanted acceptors of the P side of the main junction. Therefore, the effective doping concentration and the electric field peak value are reduced during the irradiation. Measures were performed on a single LGAD sample, progressively increasing the neutron fluence. The sample was annealed during 80 min at 60ºC between consecutive measures. It is worth to mention that the leakage current strongly increases with the irradiation neutron fluence since the damage on the high resistivity substrate tends to increase its effective doping. Nevertheless, the current leakage increase with the neutron fluence is much less than that observed in PiN diode detectors due to the counteracting effect of the multiplication degradation. It is clear that a further research effort has to be done to improve the gain reduction after irradiation by exploring the use of different implanted acceptors or by modifying the doping concentration profile.

CONCLUSIONS

The first LGAD prototypes have been designed and fabricated at the IMB-CNM Clean Room. The main challenges of the detector are the control of the multiplication factor in the core region and the different structures used as edge termination and to prevent the undesired leakage current increase due to surface inversion. Fabricated LGAD detectors exhibit a gain of 8 at a reverse bias of 300 V, compared with the commercial PiN diode detectors. The gain drastically decreases once the LGAD detector is submitted to a neutron irradiation, emulating the real operating conditions. Therefore, further work is required to optimize the performance degradation. Nevertheless, the preliminary experimental results corroborate the feasibility of using LGAD detectors in the High Luminosity Large Hadron Collider (HL-LHC).

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