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Design and fabrication of an optimum peripheral region for low gain avalanche detectors

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ABSTRACT

Low Gain Avalanche Detectors (LGAD) represent a remarkable advance in high energy particle detection, since they provide a moderate increase (gain $\sim$10) of the collected charge, thus leading to a notable improvement of the signal-to-noise ratio, which largely extends the possible application of Silicon detectors beyond their present working field. The optimum detection performance requires a careful implementation of the multiplication junction, in order to obtain the desired gain on the read out signal, but also a proper design of the edge termination and the peripheral region, which prevents the LGAD detectors from premature breakdown and large leakage current.

This work deals with the critical technological aspects required to optimize the LGAD structure. The impact of several design strategies for the device periphery is evaluated with the aid of TCAD simulations, and compared with the experimental results obtained from the first LGAD prototypes fabricated at the IMB-CNM clean room. Solutions for the peripheral region improvement are also provided.

1. Introduction

The Low Gain Avalanche Detector (LGAD) structure [1], plotted in Fig. 1, is based on the standard PiN diode architecture. Charge multiplication in LGAD is obtained by adding a moderately doped P-type diffusion (P-Well) beneath the highly doped N-type electrode, which increases the doping concentration in the vicinity of the N^+P junction with respect to the highly resistive substrate ($\rho = 10\ \mathrm{k\Omega\ cm}$). Due to P-Well diffusion, the electric field at the junction experiences a notable increase under reverse bias conditions, to such an extent that the impact ionization mechanism allows electrons generated by the incident radiation to undergo avalanche multiplication before being collected. In this respect, the LGAD performance is analogous to that of the Avalanche Photo-Diode [2] (APD), regularly used for optical and X-ray detection [3,4]. However, LGAD detectors aim at lower gain values on the output signal (in the range of 10, against typically > 100, for APD), which makes them more suitable for the tracking detection of high-energy charged particles. In the LGAD detectors the initial current is only moderately amplified in such a way that the series noise (due to the voltage) dominates over the parallel noise (due to the current), thus leading to an improvement of the signal-to-noise (S/N) ratio [5]. In high gain detectors, parallel noise becomes important and S/N would not improve with respect to a standard diode. In addition, LGAD detectors offer the possibility of having fine segmentation pitches, thus allowing the fabrication of micro-stripped or pixelated devices, which do not suffer from readout cross-talk between adjacent elements. In our design, segmented LGAD devices will only have edge termination at the last cell since the inner ones are self protected in a similar way to multicellular power MOSFETs [6].

As depicted in Fig. 1, the $P^+/\pi/P/N^+$ junction resulting from the typical LGAD structure is only implemented in the central region of the device (core region), in such a way that the area covered by the P-Well diffusion can be associated with the active area of detection. The peripheral region, extending from the core to the device edge, is considered a less efficient area in terms of detection, although it plays a crucial role to ensure the stability and uniformity of the electric field distribution within the core region. Besides, the peripheral region contributes to the reduction of the undesired leakage current collected in the N-type electrode of the detector that degrades the signal-to-noise ratio. In this respect, the design of the periphery has to provide a maximum effectiveness in terms of surface leakage reduction, optimum electric field at the core and a breakdown voltage in excess of 1000 V, which is the limit of the power supplies used in typical applications.

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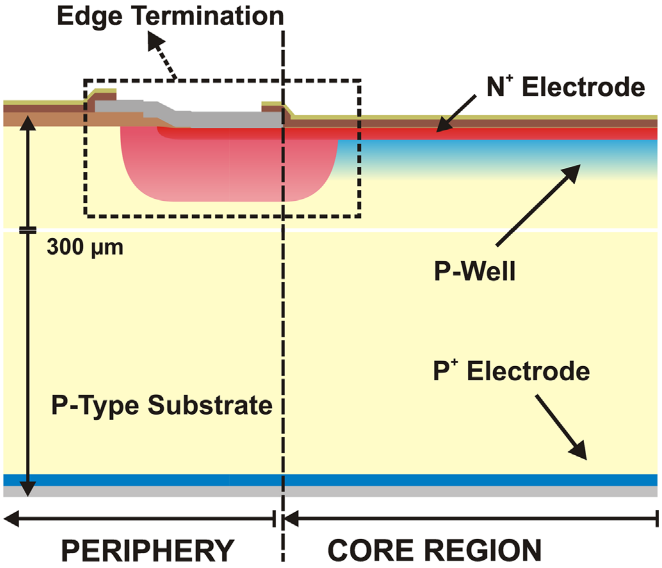

Fig. 1. Cross-section of the LGAD structure (half-cell): The $P^+/\pi/P/N^+$core region, where the multiplication takes place, covers the central area of the device. The less efficient peripheral region includes the edge termination to prevent a premature breakdown and structures to minimize the surface leakage current.

In addition, the multiplication junction requires an optimized edge termination strategy in order to prevent a premature breakdown, which would spoil the use of LGAD detectors in many applications. The performance of different edge termination designs is analyzed in Section 2.1, by evaluating their electric field profiles with the TCAD simulation software [7]. In the same way, Section 3 is dedicated to the effect of positive oxide charges and the possible technical solutions to be implemented in the peripheral region to eliminate the surface inversion layer, by its subsequent high leakage current levels. Experimental data of fabricated LGAD detectors is provided in Section 4, including the capacitive behavior. Finally, the main conclusions of the work are summarized in Section 5. The work reported in this paper has been performed in the framework of the CERN RD50 collaboration.

2. Edge termination of the multiplication junction

The multiplication junction of the LGAD detector is created by an initial Boron implantation and the subsequent high temperature anneal followed by a high dose Phosphorous or Arsenic implantation with a low temperature anneal. As a consequence, a deep P-well diffusion with a peak concentration in the range of $1 \times 10^{16}\,\text{cm}^{-3}$ and a shallow N^+ electrode diffusion are formed, leading to a $P^+/\pi/P/N^+$ structure. The resulting doping profile makes possible that, under reverse bias conditions, the electric field at the N^+P junction rises up to a value high enough to activate the impact ionization mechanism, which leads to charge multiplication However, as the same mechanism leads to the avalanche that can eventually cause the junction breakdown, the presence of the P-Well results in a significant reduction of the detector capability to stand high voltages with respect to a conventional PiN [8] design implemented on the same substrate with identical process technology except the P-Well Boron implantation.

The electric field increase is particularly critical at the N^+P junction edges, where the junction shows a cylindrical curvature, as a consequence of the planar fabrication process [9]. This behavior can be observed in Fig. 2, where the simulated electric field and electrostatic potential distributions at the N^+P junction edge are shown for the case of an LGAD detector biased at a typical operational reverse voltage of 400 V. The electrostatic potential crowds at the junction curvature which implies a local increase of the electric field in this region.

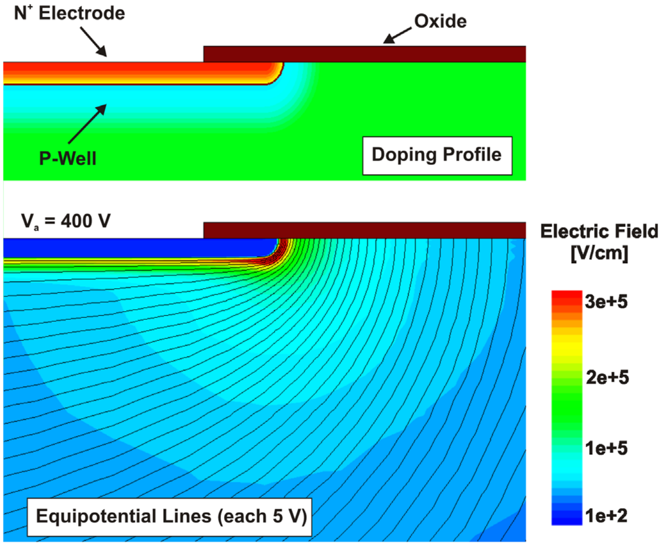

Fig. 2. Simulated doping profile (top) and electric field combined with equipotential lines distribution (bottom) at the edge termination of an unprotected LGAD multiplication junction at a reverse bias of 400 V.

The use of extremely high resistivity substrates to ensure full depletion of the detector at relatively low voltage has a direct impact on the critical electric field (E_C) value at which avalanche takes place in the different regions of the LGAD structure. The lower doped side of the N^+P junction has a peak concentration in the range of $1 \times 10^{16}\,\text{cm}^{-3}$. Taking into account the dependence of the critical electric field on the doping concentration plotted in Fig. 3, derived from [9], the E_C value is in the range of 4×10^5 V/cm. However, if no P-well diffusion is present, as in standard PiN detectors, the N^+P^- junction, with a lower doping concentration in the range of $1 \times 10^{12}\,\text{cm}^{-3}$, has an E_C value reduced to 1.5×10^5 V/cm. Therefore, the optimization of the core region edge has to consider these different values and take benefit from them to balance the breakdown point.

The modification of the electric field distribution at the junction edges might compromise the uniformity of the multiplication, as well. Charge carriers collected through the edge can have different multiplication value than those collected through the core region, where the electric field is uniform. In finely-segmented

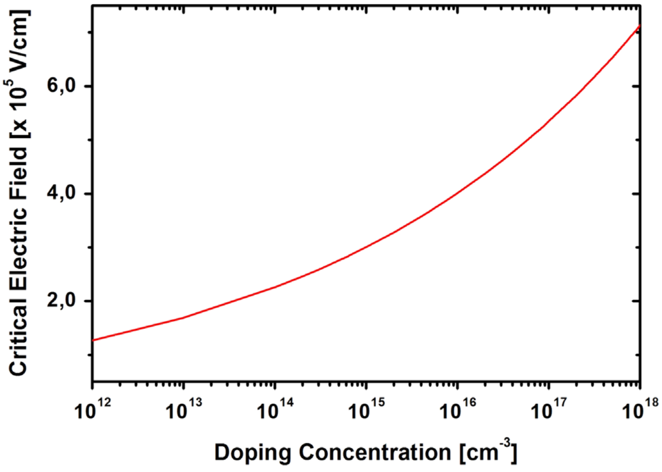

Fig. 3. Critical electric field as a function of the doping concentration, according to Baliga [7].