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A new approach to achieving high granularity for silicon diode detectors with impact ionization gain

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Abstract. Low Gain Avalanche Diodes (LGADs) are thin (20-50 μm) silicon diode sensors with modest internal gain (typically 5 to 50) and exceptional time resolution (17 ps to 50 ps). However, the granularity of such devices is limited to the millimeter scale due to the need to include protection structures at the boundaries of the readout pads to avoid premature breakdown due to large local electric fields. Here, we present a new approach – the Deep-Junction LGAD (DJ-LGAD) – that decouples the high-field gain region from the readout plane. This approach is expected to improve the achievable LGAD granularity to the tens-of-micron scale while maintaining direct charge collection on the segmented electrodes.

1. Introduction

Low Gain Avalanche Diodes (LGADs) [1, 2, 3] are a type of thin silicon diode sensor, typically implemented with an n-on-p architecture with the addition of a highly doped p+ layer just below the n-type implants of the electrodes. This additional layer, called the "gain" or "multiplication" layer, generates a high field region where controlled charge multiplication is possible, and can be up to a few microns thick. The remainder of the sensor, which is typically composed of high-resistivity silicon, is referred to as the "bulk". Owing to the intrinsic impact-ionization gain (which is typically between 5 and 50) these devices can be very thin (20-50 μm) while achieving charge collection levels greater than their much thicker conventional counterparts. This allows a short collection time with a fast rising edge that results in very precise timing information (17-50 ps) [4, 5, 6, 7, 8]. LGADs were first developed by the Centro Nacional de Microelectrónica (CNM) Barcelona, with significant participation by the RD50 Collaboration [9]. Due to their precise timing capability, LGADs offer a prospective new paradigm for space-time particle tracking [10].

To avoid breakdown between neighboring pixels, conventional LGADs make use of an inter-channel protection structure referred to as the "Junction Termination Extension" (JTE). These structures create "dead regions" of order 50-100 μm between channels, in which the charge collection is severely limited. As a result, the granularity of the LGAD sensors under development for use at the HL-LHC is limited to the millimeter scale.

Here, we present an innovative LGAD design, referred to as the "Deep Junction LGAD" (DJ-LGAD), that permits granularity on the same scale as that of conventional silicon diode sensors, while maintaining a direct coupling of the signal charge to the readout electrodes. This new design features a multiplication zone that is decoupled from the readout plane by burying a high-field diode junction several microns below the surface of the device, separated from the surface readout plane by a region for which the electric field, while still high enough to maintain drift-velocity saturation, is low enough to allow for the standard pixelization of the readout plane, and the achievement of granularity as fine as tens of microns.

2. The Deep Junction LGAD (DJ-LGAD) Concept

A schematic of the proposed doping strategy for an initial DJ-LGAD design, showing the bulk, readout, and junction regions described above, is provided in Figure 1. The semiconductor "deep-junction" is formed by abutting thin, highly-doped p+ and n+ layers, with the doping density chosen to create electric fields large enough to generate impact ionization gain in the narrow buried junction region. Additionally, the doping densities chosen for the p+ and n+ layers are balanced so that when the sensor is fully depleted, the electric field outside of the junction region, while large enough to saturate the carrier drift velocity, is significantly less than that required to create impact ionization gain. This preserves the electrostatic stability at the segmented surface of the detector, thus in principle permitting the production of DC-coupled LGADs with fine granularity.

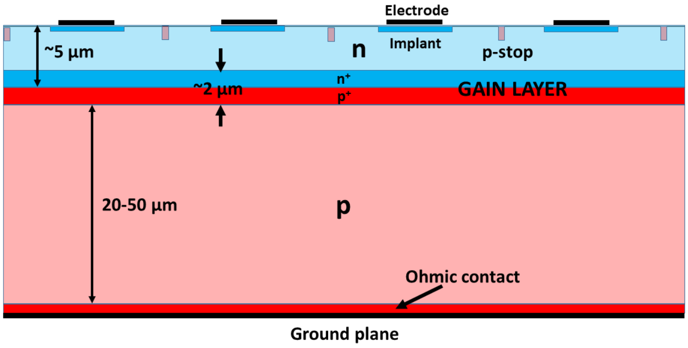

Figure 1. Schematic depiction of the DJ-LGAD concept.

3. Simulation studies

The Sentaurus simulation package [11] was used to simulate the performance of a device incorporating the doping strategy of Figure 1. Figure 2 shows the simulated strength of the component of the quiescent electrostatic field in the direction of charge collection, as a function of reverse bias voltage. For bias voltages at or above 200V, the field in the junction region reaches the values needed for generating a micron-scale avalanche. At the same time, the field strength in the bulk, and in the isolation region between the diode junction and the surface, is adequate to saturate the drift velocity for generated carriers. Figure 3 shows the expected impact-ionization gain as a function of applied voltage. Signals from minimum-ionizing particles that traverse the detector bulk are observed to peak in 300-400 psec, consistent with the peaking time of conventional LGADs with similar thickness.

In order to avoid early breakdown at the outer boundary of the sensor, fabrication of a practical semiconductor diode device requires the implementation of a junction-termination strategy. Simulation studies suggested that an "asymmetric" termination scheme, in which the n+ layer extends close to a grounded guard ring while the p+ layer terminates several microns

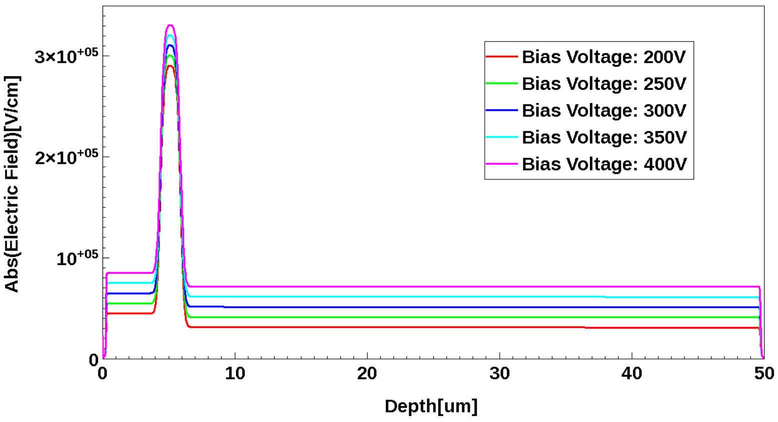

Figure 2. Simulated electric field strength along a meridian of the DJ-LGAD device that passes through the center of a channel, over a range of applied reverse bias voltages.

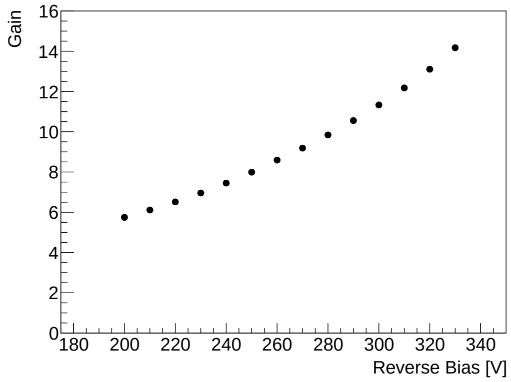

Figure 3. Simulated DJ-LGAD gain as a function of applied reverse bias voltage.

further from the sensor edge, would be likely to produce the most stable operation. Figure 4 depicts this termination scheme, as well as the electric field configuration expected to arise from it.

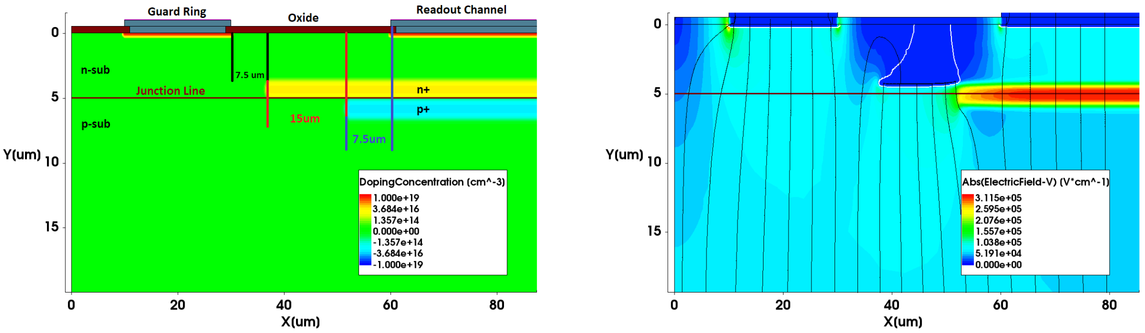

Figure 4. Doping profile cross section (left) and field map (right) for the proposed DJ-LGAD junction termination scheme.

Two different approaches to the fabrication of the DJ-LGAD are being explored. In the first, independent, opposite-polarity ion-beam doping is performed on two separate high-resistivity silicon wafers, which are then bonded to form the buried junction. In the second approach, the junction is created at the surface of a high-resistivity wafer through higher-energy boron and lower-energy phosphorus implantation runs, and then the junction is buried by depositing a high-resistivity n layer through epitaxial growth. Prototypes of both fabrication schemes are expected to be available shortly.

4. Summary

In summary, a new approach to the granularization of Low Gain Avalanche Diodes has been presented, which promises to allow for pixelization at the 10 μm scale while maintaining a direct coupling of the collected charge to the readout electrode. First prototypes of this new device, referred to as the “Deep-Junction” or “DJ” LGAD, are currently being fabricated via both wafer-to-wafer bonding and epitaxial approaches, through a collaboration between the Santa Cruz Institute for Particle Physics, Cactus Materials, Inc., and the Brookhaven National Laboratory. These prototypes should soon be available for characterization.

5. Acknowledgements

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