First Results for the pLGAD Sensor for Low-Penetrating Particles

Waleed Khalid\textsuperscript{a,}\textsuperscript{*}, Manfred Valentan\textsuperscript{a}, Albert Doblas\textsuperscript{b}, David Flores\textsuperscript{b}, Salvador Hidalgo\textsuperscript{b}, Gertrud Konrad\textsuperscript{a,c}, Johann Marton\textsuperscript{a}, Neil Moffat\textsuperscript{b}, Daniel Moser\textsuperscript{a}, Sebastian Onder\textsuperscript{a}, Giulio Pellegrini\textsuperscript{b,}\textsuperscript{*}, Jairo Villegas\textsuperscript{b}

\textsuperscript{a}Stefan Meyer Institute for Subatomic Physics, Austrian Academy of Sciences, Kegelgasse 27, 1030 Vienna, Austria
\textsuperscript{b}Centro Nacional de Microelectrónica, IMB-CNMCSCIC, 08193 Cerdanyola del Vallès, Barcelona, Spain
\textsuperscript{c}AtomInstitut, TU Wien, Stadionallee 2, 1020 Vienna, Austria

Abstract

Silicon sensors are the go-to technology for high-precision sensors in particle physics. But only recently low-noise silicon sensors with internal amplification became available. The so-called Low Gain Avalanche Detector (LGAD) sensors have been developed for applications in High Energy Physics, but lack two characteristics needed for the measurement of low-energy protons ($< 60$ keV): a thin entrance window (in the order of tens of nm) and the efficient amplification of signals created near the sensor’s surface (in a depth below 1 µm).

In this paper we present the so-called proton Low Gain Avalanche Detector (pLGAD) sensor concept and some results from characterization of the first prototypes of the sensor. The pLGAD is specifically designed to detect low-energy protons, and other low-penetrating particles. It will have a higher detection efficiency than non-silicon technologies, and promises to be a lot cheaper and easier to operate than competing silicon technologies.

Keywords: precision physics, low-energy, high efficiency, internal gain, LGAD, pLGAD

1. Introduction

Low-energy precision physics experiments investigate particles that have a low penetration depth (< 1 µm) within a detection material due to their low momenta. This fact demands specialized detection systems as the Signal to Noise Ratio (SNR) of a conventional High Energy Physics (HEP) detector is quite high to offer a good separation of the signal from the noise, e.g., for the case of aSPECT\textsuperscript{1} or Nab\textsuperscript{2} experiments. While there are detection techniques available that can be utilized for the detection of low penetrating particle such as, DEpleted Field Effect Transistors (DEPFET), Silicon Drift Detectors (SDDs) etc., they often are expensive, complicated to operate, or require cooling. As a consequence, their application is often difficult if not unfeasible for small scale experiments.

\textsuperscript{*}Corresponding author
Email addresses: waleed.khalid@oeaw.ac.at (Waleed Khalid), giulio.pellegrini@csic.es (Giulio Pellegrini)

A very promising solution to the aforementioned problem is the usage of the LGAD (Low Gain Avalanche Detector) or iLGAD (inverted Low Gain Avalanche Detector) technology. However, as the these detectors are designed for HEP applications, specific changes have to be made before such a detector can be used for the detection of low penetrating particles.

1.1. The challenge of the entrance window

When attempting to detect the signal of a low-penetrating particle, a sensor faces three distinct requirements: thin non-active layers, relatively high Charge Collection Efficiency (CCE) at the surface (as close to 1 as possible), and a readout with high SNR. A low-energy particle loses a portion of its energy within the non-active layers of the sensor and another near the surface of the silicon substrate that has a higher defect density than the bulk, and is usually heavily doped to form a field stop. Therefore, for any technology to function well for the detection of such particles, a thin entrance window
(combination of the non-active layers and the heavily doped layer of silicon with reduced CCE) is essential.

For the NoMoS (Neutron decay prOducts MOmentum Spectrometer) measurement concept [3], the benchmark is a proton with 15 keV. In this case, the maximum depth in which energy is deposited is roughly 300 nm, assuming a sensor with a thin metal passivation layer of 4 nm aluminium oxide and an incidence angle of the impinging proton of 0° (simulated 500,000 protons using IMSIL [4, 5]). IMSIL, which is binary collision Monte Carlo simulation software, was used to study the track of protons within such a detector geometry without inclusion of the electric field of the detector. Using these simulations, estimations of total number of primary e-h-pairs generated as a function of depth within the detector was obtained.

The CCE, which describes the probability that an e-h-pair survives and can be measured, is usually significantly smaller than 1 near the surface of the sensor. Therefore the combination of the signal with the CCE of the sensor, leads to a total signal that is significantly lower than that of a MIP (Minimum Ionizing Particle) traversing a standard 300 µm silicon sensor. For the NoMoS benchmark proton, approximately 4000 e-h-pairs (dividing the mean electronic energy deposited by the protons by 3.6 eV) are produced within the sensor, compared to the 24,000 e-h-pairs from a MIP.

2. A new silicon sensor concept

2.1. The pLGAD Concept

Based on the iLGAD concept [6], the proposed proton Low Gain Avalanche Diode (pLGAD) sensor concept [7] is designed with inverted doping compared to a traditional iLGAD, and takes matters two steps further: the pLGAD is equipped with a very thin, unstructured passivation layer of 4 nm of aluminium oxide (or wishfully, a thin 15 nm aluminium conduction layer) and a thin field stop in the order of 50 nm level. The sensor concept furthermore introduces a collection region by having the p-n-junction and the multiplication layer deeper in the bulk, away from the entrance window. Lastly, the polarity of the signal-collecting electrode is chosen to be an N-type, so that the signal electrons drift to the readout sensor side and cross the multiplication layer, as illustrated in Fig. 1. This also has the added benefit that thermal e-h-pairs produced within the bulk of the sensor are not multiplied as holes do not cause impact ionization when crossing the N-type multiplication layer.

In principle, the collection region defines the uniformity of the gain seen by any particle. Its depth can be adjusted by placing the gain region deeper into the sensor (via epitaxial growth) or near the unstructured entrance window (via ion implantation) during the production stage. This gives pLGAD an additional advantage of being flexible for low-energy, high precision experiments.

In the pLGAD design, only signals created close to the entrance window are amplified. This makes the sensor uninteresting for HEP applications, but perfectly suited for low-energy physics experiments.

In summary, the pLGAD concept makes clever use of two systematic asymmetries to detect low-penetrating particles: the signal created only close to the surface, and the fact that only electrons are multiplied.

2.2. Simulation of doping concentrations and breakdown voltage

In order to obtain the appropriate breakdown voltage, $V_{bd}$, and the expected gain in the pLGAD, numerical simulations using TCAD Sentaurus [8] were performed.

The key quantity for fine-tuning the operation of the sensor is the doping concentration of the multiplication layer (N-Well) as shown in Fig. 2. The
Figure 2: TCAD simulations of the expected gain and the breakdown voltage of a pLGAD sensor as a function of three different doping concentrations (represented by A, B, and C, of the multiplication N layer). The operating range refers to the desired breakdown voltage and gain.

The green area in the plot represents the operating range of interest for the sensor. This area was chosen to have the lowest $V_{bd}$ while obtaining an acceptable gain for the detection of the low-energy protons. From the preliminary TCAD simulations (Fig. 2), it could be concluded that a pLGAD with a gain of 10 and a $V_{bd}$ of 700 V can be fabricated by using an N-well doping concentration, that is represented by C in Fig. 2.

3. Characterization of first prototypes

In order to verify that the proposed sensor concept is feasible, a first production run of pLGAD sensors without a P-type collection region, a standard passivation layer of silicon nitrate albeit with a thin backplane, and shallow multiplication implant was conducted at IMB-CNM-CSIC. Four $5.3 \times 5.3$ mm$^2$ diodes from this run were chosen for initial characterization, and their current-voltage (I-V) and capacitance-voltage (C-V) curves measured, as shown in Figures 3a and 3b. From these measurements, it was concluded that the diodes reach a full depletion at $V_{bias} > 30$ V.

In order to determine the gain of the prototypes, voltage scan for one of the diodes was performed in a TCT (Transient Current Technique) setup with a blue laser of 404 nm, and an infrared laser of 1064 nm. Figure 4 shows that the diode, as opposed to a PIN diode under the same conditions, exhibits a higher gain factor for the blue laser as compared to infrared one. As the blue light (absorption length of $\approx 0.1$ cm [9]) is totally absorbed within the gain layer, it sees a higher gain compared to the infrared light (absorption length of $\approx 0.1$ cm [9]). This is a direct consequence of the polarity chosen for the pLGAD concept, as the majority of the e-h-pairs from the infrared laser are deposited within the bulk of the sensor where the majority charge carriers (electrons) drift away from the multiplication layer. The large errors bars for the blue light in Fig. 4 are due to the low signal to noise ratio for the PIN diode when measured using the TCT setup. The error bars can be reduced by bump bonding the PIN to a newer PCB and retaking measurements but are sufficient for first impressions. The complete characterization results will be published soon.

4. Possible applications

The pLGAD sensor concept allows low-energy precision physics experiments to benefit from all advantages of silicon sensors without having to sacrifice detection efficiency or spatial resolution. Its thin entrance window and internal amplification are desired in low-energy precision physics experiments. It can easily be adapted to the needs of different experiments, e.g. for the case of low-energy protons in NoMoS [3], aSPECT [1], or Nab [2].
A pLGAD sensor can be used especially but not exclusively for low-energy spectroscopy experiments with high energy resolution. The sensor works not only for protons, but also for alpha particles, low-energy ions, and with a suitable conversion layer coated on the entrance window for soft X-rays and neutrons. Furthermore, the technology can also be used for the monitoring of low-energy beam lines, for Time of Flight (TOF) experiments with a low light yield such as TOF-PET and, also for space-borne experiments.

5. Summary and Outlook

We presented a novel silicon sensor concept and selected results from its first proof-of-principle production run. The new technology is especially geared towards low-penetrating particles, with a range of below 1 µm in silicon (see Section 1.1).

The pLGAD sensor concept is a polarity-inverted iLGAD, in which only e-h-pairs created close to the entrance window are multiplied (see Section 2). Due to this the leakage current and its corresponding noise remains unamplified and the pLGAD behaves like a simple, planar sensor for high energy particles, while it offers full amplification for low-penetrating particles.

The preliminary results from the characterization of the first production run look fairly promising. A gain of 17 is obtained from a blue laser of wavelength 404 nm compared to a gain of 2 for an infrared laser of 1064 nm. Since the multiplication layer can be placed at any thickness within the sensor, future production runs will include a collection region of thickness > 0 and a thinner passivation or a metallic conduction layer. These steps will be taken as our driving application for the sensor was the NoMoS measurement concept [3], a new method of momentum-spectroscopy for the charged decay products from neutron beta decay, which requires position-resolved proton detection on a large-area sensor, at a reasonable cost. Any kind of low-penetrating particles can be detected using a pLGAD sensor, like soft X-rays, charged ions, alpha particles and with a thin conversion layer, also neutrons.

5.1. Acknowledgments

Many thanks go to Gerhard Hobler (TU Wien, Vienna, Austria) for discussions in setting up the IMSIL simulations.

The IMSIL simulations were performed using the CLIP Cluster (Vienna, Austria) [10]. This work is partially supported by the Austrian Academy of Sciences within the New Frontiers Groups Programme NFP 2013/09, the Austrian Science Fund under contract No. W1252 (DK-P1), TU Wien (Vienna, Austria) and the SMI (Vienna, Austria). This work is also partially supported by the Spanish Ministry of Science and Innovation through the Particle Physics National Program (FPA2017-85155-C4-2-R and RTI2018-094906-B-C22) and by the European Union FEDER funding program.

References

[1] M. Simson, P. Holl, A. Müller, A. Niculae, G. Petzoldt, K. Schreckenbach, H. Soltau, L. Strüder, H.-F. Wirth, O. Zimmer, Detection of low-energy protons using a silicon drift detector, Nucl. Instr. Meth. A 581 (2007) 772–775. doi:10.1016/j.nima.2007.08.156. 1, 3

[2] L. Broussard, S. Baedler, T. Bailey, N. Birge, J. Bowman, C. Crawford, C. Cude-Woods, D. Fellers, N. Fomin, E. Frlež, M. Gerike, L. Hayen, A. Jezghani, H. Li, N. Macsai, M. Makela, R. Mammei, D. Mathews, P. McGaughey, P. Mueller, D. Počanić, C. Royse, A. Salas-Bacci, S. Sjue, J. Ramsey, N. Severijns, E. Smith, J. Wexler, R. Whitehead, A. Young, B. Zeck, Using nab to determine correlations in unpolarized neutron decay, Hyperfine Interactions 240 (1) (2018) 1. doi:10.1007/s10751-018-1538-7. URL https://doi.org/10.1007/s10751-018-1538-7. 1, 3

[3] D. Moser, H. Abele, J. Bosina, H. Fillunger, T. Soldner, X. Wang, J. Zmeskal, G. Konrad, NoMoS: A drift momentum spectrometer for beta decay studies, EPJ Web Conf. 219 (2019) 04003. doi:10.1051/epjconf/201921904003. 2, 3, 4

[4] G. Hobler, Monte Carlo simulation of two-dimensional implanted dopant distributions at mask edges, Nucl. Instr. Meth. B 96 (1995) 155–162. doi:10.1016/0168-583X(94)00476-5. 2

[5] G. Hobler, K. Bourdelle, K. T. Akatsu, Random and channeling stopping power of H in Si below 100 keV, Nucl. Instr. Meth. B 242 (2006) 617–619. 2
[6] G. Pellegrini, M. Baselga, M. Carulla, V. Fadeyev, P. Fernández-Martínez, M. Garcia, D. Flores, Z. Gallaway, C. Gallrapp, S. Hidalgo, Z. Liang, A. Merlos, M. Moll, D. Quirion, H. Sadrozinski, M. Stricker, I. Vila, Recent technological developments on LGAD and iLGAD detectors for tracking and timing applications, Nucl. Instr. Meth. A 831 (2016) 24–28. doi: 10.1016/j.nima.2016.05.066.

[7] G. Pelligrini, S. Hidalgo, D. Flores, W. Khalid, M. Valentan, Low-penetrating particles low-gain avalanche detector., Patent (Pending), EP20382836.

[8] Synopsys TCAD, Sentaurus workbench, https://www.synopsys.com/silicon/tcad.html (last visited 2022-01-11).

[9] M. Green, M. Keevers, Optical properties of intrinsic silicon at 300 k, Prog. Photovolt: Res. Appl. 3 (1995) 189–192. doi:10.1002/pip.4670030303.

[10] The cloud infrastructure platform (CLIP), http://www.clip.science, last visited 2022-01-11.