Nuclear Inst. and Methods in Physics Research, A 923 (2019) 5–7

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Use of "LGAD" ultra-fast silicon detectors for time-resolved low-keV X-ray science

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ARTICLE INFO

Keywords:
Silicon sensors
Fast timing
X-ray detection

ABSTRACT

The recent development of silicon diode Low Gain Avalanche Detectors (LGADs) has opened the possibility of enhanced response and faster frame rates for the detection of X-rays produced by next-generation light sources. Preliminary results are presented on the exposure of an LGAD to a series of 500 MHz streams of X-rays with energies between 6 and 16 keV from the SLAC SSRL. X-ray absorption pulses from neighboring beam pulses, separated by 2 nsec, are well resolved. Additional results from a novel, AC-coupled LGAD, excited by a narrow infrared laser beam, indicate a point-spread function with a full width of approximately 400 μm. Further optimization of the AC-LGAD design should allow the extent of the point-spread function to be further reduced, and a granularity of $100 \times 100\ \mu m^2$ or finer to be reached.

Contents

1. Introduction

The recent development of silicon diode Low Gain Avalanche Detectors (LGADs) has enabled the design of granular ($\sim$1 × 1 mm^2) fast-timing layers for the ATLAS and CMS tracking systems at the HL-LHC. These systems will permit the determination of the time-of-passage of minimum ionizing particles to a precision of better than 50 ps [1]. Fig. 1 shows the essential design aspects of the LGAD: a region "P" with a dopant concentration significantly greater than that of the bulk "π" region leads, after depletion, to an electric field large enough to provide amplification (by as much as a factor of 70) through multiplication of the signal. Because of this amplification, the "π" region can be made very thin (50 μm or less), leading to a fast signal and, in turn, precise timing.

Recently, groups developing LGADs for use in these particle physics applications have begun to explore the possibility of their application to other fields of science and technology [2]. In particular, the group at SCIPP has become interested in the possible use of LGADs in the development of X-ray cameras with frame rates in excess of 100 MHz. This proceeding presents a number of preliminary results arising from the first exposure of LGADs to an X-ray beam. The beam, delivered by the high repetition-rate SLAC SSRL, was delivered with a series of energies between 6 and 16 keV, and directed on an LGAD with a 50 μm bulk thickness designed and fabricated by the Hamamatsu Corporation. Three neighboring pixels were bonded out individually to custom-designed amplifier circuitry with a 2 GHz bandwidth. Amplified signals were digitized and acquired by a digital storage oscilloscope with a 2.5 GHz bandwidth.

2. The AC-coupled LGAD

With the current state of development, the electric field in the region adjacent to the "P" implant is significantly distorted, leading to charge-collection deficits that limit the efficiency of the device for cell sizes less

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https://doi.org/10.1016/j.nima.2019.01.050
Received 13 November 2018; Received in revised form 12 January 2019; Accepted 16 January 2019
Available online 19 January 2019

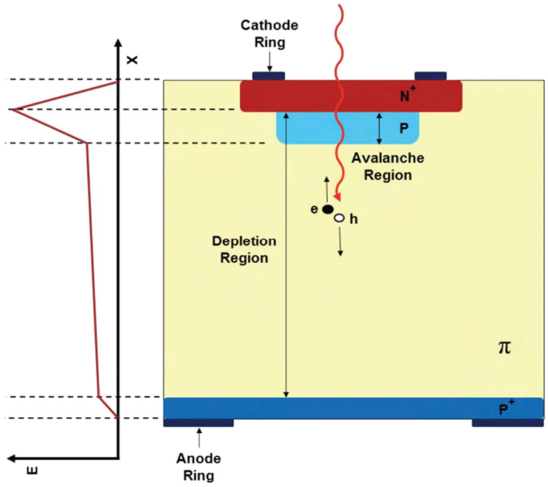

Fig. 1. Essential design aspects of the Low Gain Avalanche Detector. The blue "P" region has significantly higher doping than the bulk "π" region, leading after depletion to an electric field large enough to provide amplification through multiplication of the signal . (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

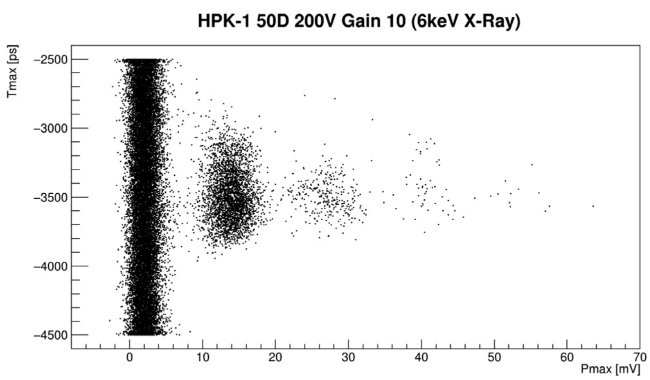

Fig. 2. Two-dimensional distribution of pulse time versus pulse height for an exposure of the conventional LGAD to a 500 MHz stream of 6 keV X-rays.

than 1×1 mm^2 [3] . This can be avoided by maintaining a fully planar geometry for the avalanche ("P") and junction ("N$^+$") implants. In order to maintain the granularity of the readout, a passivation layer can be grown above the implant, on top of which a patterned metallization layer can be deposited. The signals are then capacitively coupled to the metalized layer, with a point-spread function that depends on the resistivity of the implant. In this way, the granularity of the metalized layer of the resulting "AC LGAD" [4] can be made much finer than the 1×1 mm^2 scale of the conventional LGAD, which is an essential requirement for photon science applications [5]. The AC LGAD results reported here were obtained for a sensor with a bulk thickness of 100 μm, a pixel size of 500×500 μm^2, and an implant resistance of 115 Ω/□, via illumination with an infrared laser with a spot diameter of approximately 25 μm.

3. Preliminary energy response

Fig. 2 shows the two-dimensional distribution of pulse time versus pulse height for an exposure of the conventional LGAD to a 500 MHz stream of the lowest energy X-rays (6 keV) received from the SSRL. Well-delineated regions corresponding to no absorbed photon (vertical strip), one photon (darker concentration to the right of the strip), two, three and four photons are observed in the distribution.

Fig. 3 shows the pulse-height distribution obtained by selecting events only in the first (one-photon absorption) concentration of events

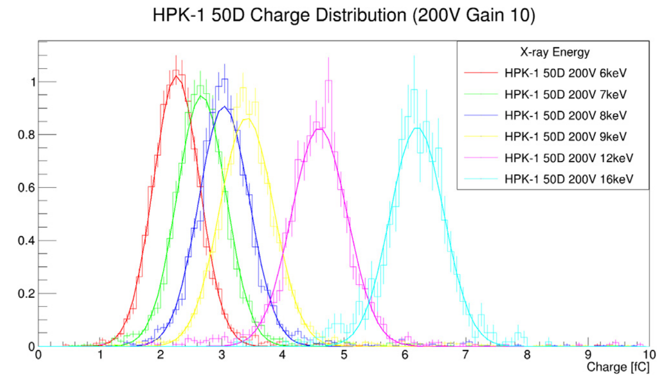

Fig. 3. Pulse-height distribution obtained by selecting events only single-absorption events, as described above, for each of the SSRL beam energies studied during the run.

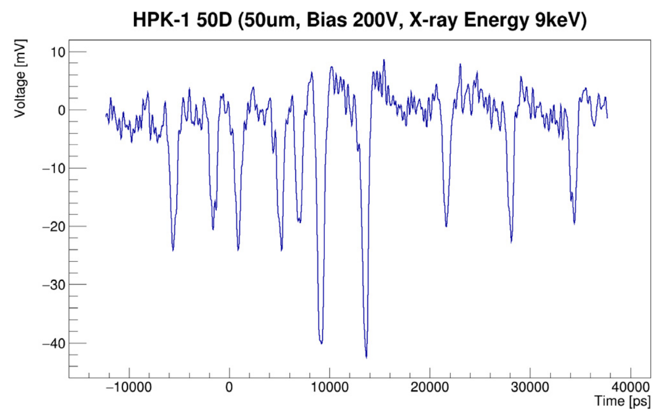

Fig. 4. Temporal response of a conventional LGAD to a 500 MHz stream of 9 keV photons produced by the SLAC SSRL.

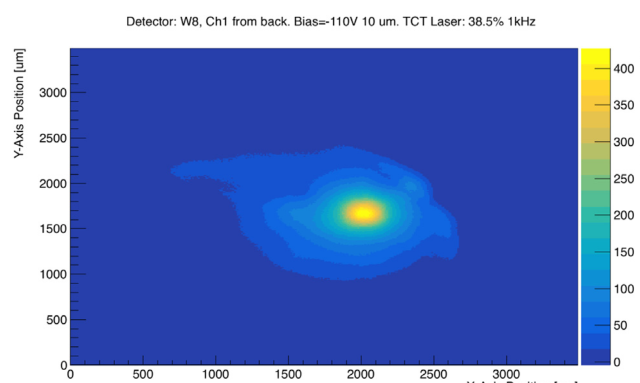

Fig. 5. Response of the AC LGAD sensor to excitation with the precision infrared laser, as a function of the position of the laser spot on the sensor. The sensor had a bulk thickness of 100 μm, an electrode pixel size of 500×500 μm^2, and a sheet resistance of 115 Ω/□.

for each of the SSRL beam energies studied during the run. The width of the nearly-Gaussian distributions reflect a fractional energy resolution of between 8% (for 16 keV X-rays, the highest energy provided to us by the SSRL) and 15% (for 6 keV X-rays). More study will be needed to come to an understanding of what the dominant contributions to the line width are (electronic noise, energy deposition statistics, etc.).

4. Temporal response

Fig. 4 shows a typical oscilloscope trace for an exposure of a conventional LGAD to the 500 MHz SSRL beam, set to an energy of 9

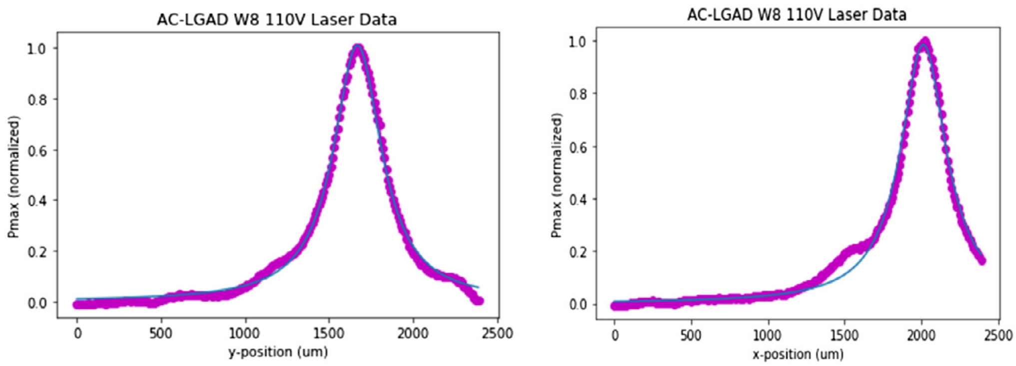

Fig. 6. Point-spread function for an AC LGAD with a bulk thickness of 100 μm, a pixel size of 500 × 500 μm^2, and a sheet resistance of 115 Ω/□.

keV. Although not all of the buckets show a response to X-ray absorption (as expected from the typical absorption-number distribution implied by Fig. 2), there are a number of pulses separated by the 2 nsec beam-delivery period. For those cases, there is a clear temporal separation between successive pulses. In addition, offline studies have observed no diminution in response for pulses immediately following an occupied bucket relative to those that follow a bucket showing no response. The sensor system, which has not been optimized for maximal repetition rate, is seen to be capable of separating X-ray events at rates higher than the 500 GHz repetition rate of the SSRL beam.

5. AC LGAD point-spread function

The width of the SSRL beam used for the LGAD studies presented above was too broad to permit a determination of the point-spread function of the AC LGAD signal. Instead, an infrared laser with a beam width of 25 μm was scanned across the back face of the sensor, and the pulse height in one of the sensor pixels was determined as a function of the position of the laser beam (see Fig. 5). The sensor had a bulk thickness of 100 μm, an electrode pixel size of 500 × 500 μm^2, and a sheet resistance of 115 Ω/□.

The response is projected separately into the x and y directions in Fig. 6. From these distributions, the full width of the AC LGAD point-spread function is seen to be approximately 400 μm. This could be reduced by increasing the implant resistance.

6. Summary

The recent development of solid-state Low Gain Avalanche Detectors (LGADs) may offer a new approach to the detection of X-rays that enhances both the sensitivity and frame rate relative to existing detection systems. An LGAD with a bulk thickness of 50 μm was illuminated by streams of X-rays with energies between 6 and 16 keV, exhibiting a rate capability in excess of the 500 MHz repetition rate of the X-ray beam, and a fractional energy resolution in the 10% range. The dominant contribution to the line width has yet to be determined; further study may allow improvements in the energy resolution. AC-coupled LGADs offer the possibility of granularity in the 100 × 100 μm^2 range. Studies of an AC-coupled LGAD with an implant resistant of 115 Ω/□, making use of a precision infrared laser, indicated a point-spread function with a full width of approximately 400 μm. The width of the point-spread function could be reduced by increasing the implant resistance.

Acknowledgments

The authors would like to acknowledge the Office of Research Industry Alliances and Technology Commercialization, USA of the University of California at Santa Cruz, and the Hamamatsu Corporation, USA, for their generous support of the Launchpad initiative "Radiation Hardened AC Ultra-Fast Silicon Detectors (UFSD)". The authors would also like to acknowledge the SLAC National Accelerator Laboratory and its staff for providing us the opportunity to expose our LGAD prototype sensors to the SSRL X-ray beam.

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