ARTICLE IN PRESS

Nuclear Instruments and Methods in Physics Research A ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

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

Ultra-fast silicon detectors (UFSD)

H.F.-W. Sadrozinski [a,*], A. Anker [a], J. Chen [a], V. Fadeyev [a], P. Freeman [a], Z. Galloway [a], B. Gruey [a], H. Grabas [a], C. John [a], Z. Liang [a], R. Losakul [a], S.N. Mak [a], C.W. Ng [a], A. Seiden [a], N. Woods [a], A. Zatserklyaniy [a], B. Baldassarri [b], N. Cartiglia [b], F. Cenna [b], M. Ferrero [b], G. Pellegrini [c], S. Hidalgo [c], M. Baselga [c], M. Carulla [c], P. Fernandez-Martinez [c], D. Flores [c], A. Merlos [c], D. Quirion [c], M. Mikuž [d], G. Kramberger [d], V. Cindro [d], I. Mandić [d], M. Zavrtanik [d]

[a] *SCIPP, Univ. of California Santa Cruz, CA 95064, USA*
[b] *Univ. of Torino and INFN, Torino, Italy*
[c] *Centro Nacional de Microelectrónica (CNM-CSIC), Barcelona, Spain*
[d] *IJS Ljubljana, Slovenia*

ARTICLE INFO

Article history:
Received 25 November 2015
Received in revised form
22 March 2016
Accepted 29 March 2016

Keywords:
Fast silicon sensors
Charge multiplication
Thin tracking sensors
Silicon strip
Pixel detectors

ABSTRACT

We report on measurements on Ultra-Fast Silicon Detectors (UFSD) which are based on Low-Gain Avalanche Detectors (LGAD). They are n-on-p sensors with internal charge multiplication due to the presence of a thin, low-resistivity diffusion layer below the junction, obtained with a highly doped implant. We have performed several beam tests with LGAD of different gain and report the measured timing resolution, comparing it with laser injection and simulations. For the 300 μm thick LGAD, the timing resolution measured at test beams is 120 ps while it is 57 ps for IR laser, in agreement with simulations using Weightfield2. For the development of thin sensors and their readout electronics, we focused on the understanding of the pulse shapes and point out the pivotal role the sensor capacitance plays.

1. Introduction

We propose an ultra-fast silicon detector that would establish a new paradigm for space-time particle tracking [1]. Presently, precise tracking devices determine time quite poorly while good timing devices are too large for accurate position measurement. We plan to develop a single device that ultimately will measure with high precision concurrently the space (~10 μm) and time (~10 ps) coordinates of a particle.

First applications of UFSD are envisioned in LHC upgrades, in cases where the excellent time resolution coupled with good spatial resolution helps to reduce drastically pile-up effects due to the large number of individual interaction vertices. While ATLAS is proposing UFSD as one of the technical options for the High Granularity Timing Detector (HGTD) located in front of the forward calorimeter (FCAL), CMS-TOTEM are considering UFSD to be the timing detectors for the high momentum - high rapidity Precision Proton Spectrometer (CT-PPS), residing in Roman-pots about 200 m from the interaction region. In both cases, the UFSD would be of moderate segmentation (a few mm^2) with challenging radiation requirements (few times 10^{15} neq/cm^2), requiring a time resolution of 30 ps, which could be achieved by stacking up in series up to four sensors.

UFSD are thin pixelated n-on-p silicon sensors based on the LGAD design [2,3] developed by CNM Barcelona. The LGADs exhibit moderate internal gain (~10*x*) due to a highly doped p+region just below the n-type implants. Based on the progress made through 7 fabrication cycles, the performance of LGAD have been established in several beam tests and with laser laboratory measurements. The sensors tested were routinely operated for long time periods at an operating bias voltage close to 1000 V for 300 μm thickness (500 V for 50 μm) and various internal gains of 3–20.

Since present experience with LGAD is limited to sensors with 300 μm thickness [4], a reliable tool is needed to extrapolate their performance to the planned thickness of 50 μm. This is done with the simulation program *Weightfield2* (WF2) [5] that has been developed specifically for the simulation of the charge collection in semiconductors. In the following, we compare the pulse shapes of thick and thin LGAD to elucidate the advantage of thin sensors, including those due to trapping effects after irradiation. This is followed by an introduction to precision timing in silicon detectors and a prediction of the expected timing resolution as a function of LGAD thickness and internal gain. The predictions will be

---

[*] Corresponding author.
E-mail address: hartmut@ucsc.edu (H.-W. Sadrozinski).

http://dx.doi.org/10.1016/j.nima.2016.03.093
0168-9002/© 2016 Elsevier B.V. All rights reserved.

Please cite this article as: H.-W. Sadrozinski, et al., Nuclear Instruments & Methods in Physics Research A (2016), http://dx.doi.org/10.1016/j.nima.2016.03.093

confronted with results from several beam tests and laboratory laser measurements. Finally we present pulse shapes on thin LGADs and the pivotal role the sensor capacitance plays in the timing resolution of UFSD.

2. LGAD pulse shapes

The *Weightfield2* program [5] simulates the electrostatic fields and the charge collection in LGAD, including the effect of the internal gain. The current output of the sensor can then be convoluted with the response of the front-end electronics generating a voltage signal that can be used to evaluate the timing capabilities of a detector. Fig. 1.a shows the output current for a minimum ionizing particle (MIP) traversing a 50 µm thick LGAD with gain 10 biased at large over-depletion, showing the separate contributions from the drift of both the initial and gain electrons and holes, respectively. For thicker LGAD, the current pulse has the same shape as that shown in the picture, with the only difference that the pulse duration is scaled by the thickness, i.e. the 1 ns collection time for the 50 µm thick LGAD becomes 9 ns for 300 µm thickness. In Fig. 1.b the voltage signals from a broad-band amplifier (BB) are shown for LGADs of different thickness, indicating that for constant gain the maximum pulse height is independent of the LGAD thickness, and that the shorter rise time favors the thin sensor for timing application.

The change of the LGAD pulse shape due to trapping after irradiation can be studied with WF2, of which version 3.5 incorporates trapping [6]. Since the characteristic trapping time is about 0.5 ns (corresponding to a trapping length of ~50 µm), on comparing the signals from thin and thick detectors shown in Fig. 1.b one would expect that the longer pulses of thick detector will be effected much more by trapping than the short ones from thin LGAD. This is illustrated in Fig. 2 where the BB pulses for LGAD with gain 10 and thickness a) 300 µm and b) 50 µm, respectively, (note the different time scale) are shown for different neutron fluences. For 300 µm LGAD (Fig. 2.a), the large loss of gain holes changes the pulse shape drastically and reduces the observed gain (defined as the ratio of pulse areas of LGAD over that of no-gain diodes) by a large amount. The effect of trapping on thin sensors is much less drastic as shown in Fig. 2.b: the pulse shape and the rising edge are preserved (which is good for timing) and the gain loss is limited.

For timing application, the pulse amplitude is more important than the pulse area. The variation of signal amplitude as a function of neutron fluence is shown in Fig. 3 for 300 and 50 µm thick LGADs: up to a fluence of 4 × 10^{15}, the pulse height loss due to trapping for a 50 µm thick LGAD is less than 50% of its pre-rad value.

The mechanisms underlying the radiation effects in LGADs are under intensive investigation within RD50 [7]. Up to now, data are available for 300 µm thick LGAD, and the data are interpreted in terms of a decrease in the gain in addition to the signal decrease caused by trapping at fluences beyond 10^{14} neq/cm^2 [8]. This has been identified with an initial acceptor removal, depending on both the boron doping concentration and the interstitial defects created during irradiation [9]. The acceptor removal appears to level off at higher fluences so that a gain of about 3.5 is observed at a fluence of 2^*10^{15} neq/cm^2, for which we project a timing resolution of about 60 ps, using Figs. 4 and 7 and assuming that the timing resolution scales with d*V*/d*t*. We are fabricating thin sensors with a variety of gain values and bulk resistivities for irradiations to verify the acceptor removal model. In addition, we are working on replacing the boron in the multiplication layer by gallium, which has been shown to be more radiation resistant.

3. Simulation of the UFSD timing resolution

We have used WF2 to simulate LGAD parameters which drive the timing resolution: internal gain, capacitance and thickness. The time resolution σ_t is given by contributions from time walk, jitter and TDC binning:

$$\sigma^2{}_t = \left(\left[\frac{V_{th}}{dV/dt}\right]_{RMS}\right)^2 + \left(\frac{N}{dV/dt}\right)^2 + \left(\frac{TDC_{bin}}{\sqrt{12}}\right)^2$$

with V_{th} the signal threshold, d*V*/d*t* the signal slope or slew-rate, *N* the noise, and TDC$_{bin}$ the size of a TDC bin, indicating the central role of the slew-rate of the signal dV/dt [10]. This means that we need both large and fast signals. We are still quantifying the contributions to the time resolution due to the non-uniform charge deposition within the sensor caused by local Landau fluctuation (in addition to the standard time-walk contribution), and will report on this issue soon in a separate paper. Using WF2, we can show that the time resolution improves with larger gain as well as with thin detectors (Fig. 4), since both increase the slew-rate. An additional advantage is expected from sensors with reduced capacitance, i.e. small area, as they permit larger slew-rate for a fixed input impedance of the amplifier (see Section 5 below).

4. Timing resolution measurements

We measured the time resolution of 300 µm thick LGAD pads

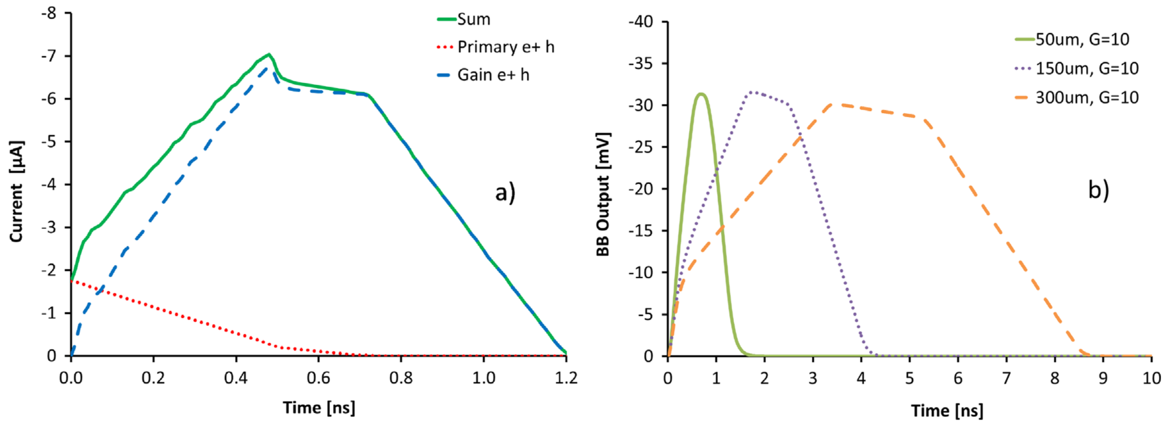

Fig. 1. Pulse shapes of LGAD simulated with WF2 version 3.5: a) detector current for a MIP traversing a 50 µm thick LGAD; b) voltage output from a x100 broad-band amplifier (BB) with 50 Ω input for LGADs with gain of 10 and thickness 50, 150, 300 µ [5].

Please cite this article as: H.-W. Sadrozinski, et al., Nuclear Instruments & Methods in Physics Research A (2016), http://dx.doi.org/10.1016/j.nima.2016.03.093