Generic EIC Detector R&D Proposal: Fabrication and characterisation of the Trench Isolated Low Gain Avalanche Detectors for 4D tracking

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14th July 2023

Abstract

We propose to develop and characterise Trench Isolated LGAD (TI-LGAD) sensor technology to determine its utility for 4D tracking detectors. EIC detector sub-systems in the Far-Backward and Far-Forward region such as the Low-Q^2 Tagger and B0 tracker are required to handle very high rates and reconstruct particle tracks with minimal timing and spatial resolution. The work carried out in this proposal will explore the improvements seen when using TI-LGAD sensors, coupled to appropriate readout, for these and other detector sub-systems. Funds are requested to design, fabricate and test TI-LGAD prototypes, tailored for applications at the EIC, including those bonded to TimePix4 ASICs.

1 Introduction

Creating detectors with precise 4D charged particle tracking has become a necessity for the next generation of nuclear and particle physics experiments. The EIC has been designed to provide an ambitious interaction luminosity allowing access to otherwise immeasurable physics. These goals require the high rate, unambiguous separation of signals from different sources such as; particle tracks from a collision, particles originating from different interactions, and backgrounds to be identified and eliminated. In order to realise the requirements for some of the detector sub-systems, detectors with high spacial and temporal resolution (4D detectors) are required.

The state-of-the-art in 4D detectors are pixellated Low Gain Avalanche Detectors (LGADs). These devices can provide a timing resolution of order 30 ps for areas down to the order of 1mm^2. The pixel pitch of the base LGAD design is restricted by an additional doping electrode around each pixel to mitigate excessively high field at the perimeter of the multiplication junction, known as junction terminating electrodes (JTEs). The JTEs change the collection field and reduce the amplification fill factor which results in pixels below 500 μm effectively being unviable. A number of adaptations to the original LGAD design have been proposed as solutions to the low fill factor when the pixel pitch is reduced. Each design has unique features which may be beneficial or detrimental depending on the requirements of the detector system, comparisons of the technologies can be found in [1].

This proposal seeks to advance the development of the TI-LGAD technology, focusing on detector applications at the EIC. The work will build on an existing experience of the Glasgow Group. In collaboration with Micron Semiconductors Ltd. we successfully fabricated and tested two generations of LGADs: conventional devices with JTEs [2, 3] and Inverse LGADs [4]. In this proposal we seek funds to produce and characterise the TI-LGAD technology.

The end goal of this proposal is to fabricate and characterise a TI-LGAD coupled to an TimePix4 ASIC [5] - a highly complementary work to our ongoing TimePix4 ePIC Low-Q^2 tagger activity.

2 The Role of 4D Detectors at EIC

The ePIC Far-Forward (Off Momentum Detector, Roman Pots and B0) and Far-Backward (LowQ^2 Tagger and Luminosity Pair Spectrometer) tracking detectors (Figure 1) are highlighted here as the main potential benefactors of the work outlined in this proposal. These detectors are expected to see the highest flux density of the ePIC detector systems with high background rates, in order to handle this they are designed with high granularity silicon pixel detectors. While the $\sim$2 ns timing resolution of a standard silicon sensor is sufficient to separate out hits from bunch crossings separated by 10 ns, upgrading to an LGAD sensor would vastly improve their capacity to filter out backgrounds from the interesting physics tracks which in turn reduces the running period needed to

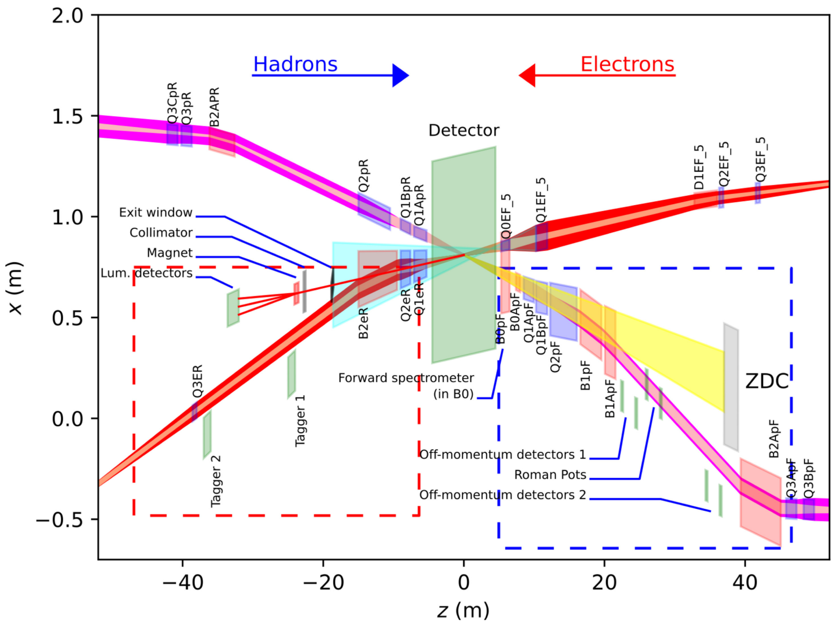

Figure 1: Layout of EIC IP6 interaction region where the ePIC detector is to be located. The red and blue boxes respectively contain the far-backward and far-forward detectors discussed in this proposal.[6]

obtain results of desired precision.

Compared with traditional silicon sensors, an LGAD based device provides a number of benefits for tracking detectors:

- LGAD can be much thinner than conventional Silicon, due to the large signal size achieved in avalanche mode.
  - Reduced multiple scattering of MIPs allowing more precise track reconstruction.
  - Reduced charge collection time so the rate threshold for signal pileup is higher.
  - Lower efficiency of background neutral particle interactions.
- Faster timing resolution.
  - Can be used for time of flight track hit matching (4D detector).
  - Better rejection of out-of-time backgrounds.

The EIC has different proposed structures for the electron and ion bunches [7], the electron bunch will have a length RMS of 0.7 cm while the proton bunch will be 7 cm. At the speed of light these distances, respectively, are equivalent to 23 ps and 233 ps. The 30 ps resolution of LGAD technologies serves a different primary function in the far-forward and far-backward regions. For the far-forward detectors it helps determine where within the ion bunch an interaction occurred. For the shorter electron bunch this will have very limited resolving power, instead the fast timing resolution provides the far-backward detectors with a very narrow signal window which will be indispensable for background rejection.

Along with particle reconstruction, the far-forward sub-systems are required to serve the dual function of localising the interaction vertex by providing precise timing information [8]. To meet this requirement, the baseline detectors plan to use AC-LGADs as timing layers. The use of AC-LGAD for precise spatial tracking relies on charge sharing of the signal among several neighbouring 500 μm pixels, this limits flux density of the detector with no two particles within order a few mm being separable [9]. There are also open questions to how the spacial resolution of the AC-LGAD will degrade as radiation damage reduces the signal amplification of the sensor. Alternative technologies with smaller pixel pitches are being considered for tracking layers and future upgrades. The TI-LGAD would be able to simplify the detectors with a single solution for combined tracking and timing layers.

The position of interacting electrons within a bunch cannot be well resolved with an LGAD. Being able to resolve the TOA of a particle to 30 ps would instead serve the essential purpose of separating out-of-time backgrounds. Any signal coming from outwith a $\sim$100 ps coincidence window can be excluded, sources of these background hits expected to have a significant rate include:

- Scattered synchrotron radiation with a path length more than 3 cm longer than the electrons.
- Interactions from satellite bunches.
- Background from the tunnel/ion beamline.

In the far-backward region, the LowQ^2 tagger is expected to see the highest rates of any ePIC tracking detector, in its hottest region this has been simulated as up to the order of 100 kHz per 55 μm pixel, primarily coming from Bremsstrahlung electrons. An LGAD sensor over standard silicon here will be able to take advantage of the reduced charge collection time minimising the signal pile up while keeping above the electronic noise. The high occupancy of the detector makes track identification and reconstruction computationally challenging, the capacity to filter hits from out-of-time background sources is a very powerful way of reducing this at the first stage.

The luminosity Pair Spectrometer tracker is the other detector in the far-backward region which could benefit from the increased timing separation provided by LGAD sensors. Understanding and subtracting the backgrounds laid out previously is key to a high precision measurement of the interaction luminosity, this can only be achieved if discrete background samples can be resolved separately from the primary interaction peak.

3 Trench-Isolated LGAD

LGAD sensors were first demonstrated 10 years ago to achieve a timing resolution of 30 ps [10], this is achieved by amplifying the signal in a high doped layer, creating an avalanche of additional electrons in a strong field, generating a sharp signal rise time. The LGAD original design requires a Junction Termination Extension (JTE) at the edge of the gain implant region resulting in a field profile where charge deposited close to the edge experiences no amplification. This is not a problem for large area LGAD sensors as the edge effects have a minimal effect on the overall fill factor, however, when attempting to shrink the design for use in pixel detectors of the 100 μm scale the fill factor effectively reduces to 0% [11].

A number of adaptations to the LGAD, proposed to address the pixel size limitations are seeing a period of rapid development [1]. Characteristics of the Trench-Isolated LGAD design most closely match those essential for operation in a high rate environment, namely the isolation limits the sharing of charge between pixels so fewer signals need to be read out per hit and the detector occupancy is kept lower. Figure 2 shows the implantation structure difference between the original LGAD and TI-LGAD designs, illustrating how the no-gain region has been reduced. The JTE design has a minimum region of 20 μm between neighbouring pixel multiplication implants where there is no gain. The trench isolation reduces this distance to 2 to 3 μm. The no-gain region of the JTE design is even larger than the geometric limitation as the JTE is, by design, a deep junction and this preferentially collects charge for tracks incident under the multiplication implant. This further reduces the gain geometric fill factor of a device for example a device with a 200 μm pixel pitch reduces from 60% geometric to 40% amplification gain fill factor. No such effect is present in the trench isolated design.

For a 100% fill factor, the two alternative proposed LGAD designs, besides TI-LGAD, are the inverse LGAD (iLGAD) and the AC-coupled LGAD. The iLGAD moves the gain region to the non-pixellated backside of the device. This device requires double-side device fabrication which adds complexity to the fabrication, post-processing and subsequent the device handling. The requirement to make a 50 μm thin device, for fast signal collection, requires the use of handling wafers for iLGADs during the fabrication process which increases still further complexity and price; and reduces yield. A module consisting of an iLGAD coupled to the TimePix3 chip has successfully demonstrated 100% fill factor with 55 μm pixel pitch [4]. The AC-LGAD, as mentioned above, has issues with high flux environments due to the $O(10)$ ns long signal duration and radiation resistance and is therefore not ideal for the EIC application. The TI-LGAD requires an additional fabrication stage over the original LGAD design; namely the trench etch and oxidization, however this is not an issue. The trench is only a few micrometers deep and has an aspect ratio of no more than 3:1, which is not demanding for today's deep silicon etch technology.

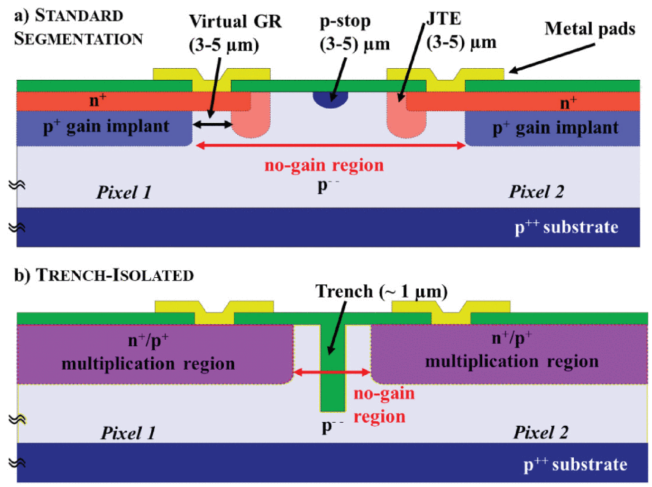

Figure 2: Comparison of standard and TI-LGAD structures, taken from [12]

3.1 Research Status

TCAD simulations of the TI-LGAD [13] have demonstrated the trench provides the required pixel isolation and prevents early breakdown due to high fields at the edge of the multiplication implant. These characteristics are maintained even after irradiation. The simulation showed that a trench of 3 μm depth and width of 2 μm is sufficient.

Fabrication and characterisation of simple 2 pixel TI-LGADs has been conducted by FBK laboratories and the CERN RD50 collaboration [14, 15] of which authors of this proposal are members. Additional devices have been designed by the authors and fabricated by Micron Semiconductor Ltd[1]. Characterisation of the first devices is about to commence at Glasgow University. The work at Glasgow extends the research beyond that performed at FBK on the characterisation of the trench isolation in a simple 2 pixel to investigate pixel arrays and different substrates. Additionally the work adds a second device fabrication vendor for TI-LGADs for the scientific community.

Ongoing research into TI-LGADs at the University of Glasgow, in collaboration with industry partner Micron Semiconductors, is at a stage where funds from the generic EIC-related detector R&D program would accelerate the progress and provide focus on the ePIC/second detector requirements.

A current generation of TI-LGADs have been designed with a 55 μm pixel pitch to match that of TimePix3 and MediPix3 ASICs. Without charge sharing, the position resolution of a 55 μm pitch pixel detector is given by 55 $\mu m/\sqrt{12} = 16\ \mu m$, TI-LGAD devices demonstrate limited charge sharing between pixels which will improve on this slightly, while keeping the data rate low and flux capacity high. The TimePix4 ASIC is already the technology of choice for use

[1]Micron Semiconductor Ltd, Sussex, U.K. *http://www.micronsemiconductor.co.uk/*

in the Low-Q^2 tagger. New TI-LGAD devices that match the larger TimePix4 ASIC are required.

The advantages of high granulation sensors for 4D tracking at the EIC are clear, the TI-LGAD is a promising candidate which is worth pursuing the development of.

4 Developing and Testing TI-LGAD Sensors

An initial batch of TI-LGADs is in production at Micron Semiconductors Ltd. This consists of two wafer substrates (250 μm thick high resistivity float zone and 50 μm thick high resistivity epitaxial on a conductive 500 μm thick silicon support wafer) with a range of device designs. The designs include test diodes with different trench isolation characteristics and pixel arrays matched to the TimePix3 ASIC. There are array designs with a pixel pitch of 55 μm and 110 μm.

The wafer design was performed at Glasgow University informed by TCAD device simulation. The majority of the device fabrication is performed at Micron Semiconductors Ltd. However the trench etch is performed at the Scottish Microelectronics Center, SMC, in Edinburgh working in close collaboration with Glasgow University and Micron Semiconductor Ltd. The trenches are filled with thermal oxide at after etching and all subsequent processing takes place at Micron Semiconductor Ltd. An agreement exists between the University of Glasgow, Micron Semiconductors Ltd., and the SMC to produce 12 float zone wafers and 6 epitaxial wafers with trenches.

Characterising the properties of the TI-LGADs produced by Micron and the SMC and testing a sensor bonded to a TimePix3 and TimePix4 ASICs form the main proposed work package for the named participants. Measurement of position dependant gain, timing resolution and charge sharing/position resolution will be made and compared to simulations carried out with TCAD. The existing wafers will allow the testing of TimePix3 devices, while a subsequent sensor fabrication round is required to test TimePix4 compatible devices.

The characterisation of the devices is summarised as follows:

- Initial wafer level electrical characterisation on a probe station.
  - Sensor IV and CV characteristics measured
  - Gain layer depletion, full device depletion and breakdown voltages determined
  - Doping density profile measured
- Post processing for flip-chip bonding to TimePix3 ASIC
  - Under Bump Metallisation, (UBM), deposited on sensor wafer
  - Sensor wafer diced
  - Flip-chip bonding to TimePix3 ASIC

  - Assembly of modules

- Radiation response tests of diodes
  - Initial electrical characterisation of diced diodes
  - Gain of the didoes measured using the transient current technique, TCT
  - Timing resolution of the diodes measured using Sr-90 source and single channel amplifiers
  - Measurement of signal isolation of trench made
  - Measured performed for temperatures from -30C to +20C
  - Measurements repeated after exposure to irradiation

- Radiation response tests of modules
  - Initial electrical and X-ray source characterisation of module performed
  - Characterisation of the module for in-pixel gain measurements at the Diamond Light Source
  - Measurement of the spatial and temporal resolution at a high energy particle test beam using a telescope
  - Measurement of charge sharing and detection efficiency using a high energy particle test beam using a telescope

4.1 Equipment and techniques

4.1.1 Laboratory equipment and techniques

The Glasgow laboratory has the necessary equipment and expertise to perform all the laboratory based measurements.

Our facilities has a semi-automatic probe station with thermal chuck coupled to electrical characterisation equipment to allow wafer level temperature controlled electrical characterisation.

The laboratory has a Transient Current Technique (TCT) system with both red and infrared lasers for the measurement of the gain of the device. The system has a beam spot width of 5 μm which allows sub-diode gain mapping to be performed. This has an integrated Peltier cooler to allow measurements down to -30°C.

The laboratory has a timing system based on single channel amplifies that has measured the timing resolution of LGAD diodes to $O(10)$ ps. This is housed in an environmental chamber to allow measurements down to -30°C.

4.1.2 TimePix DAQ

The Glasgow group is a member of all the TimePix collaborations [16]. It has a range of DAQ systems for the different chip generations, including the SPIDR4 system for latest TimePix4 chip. The group has a wealth of experience in characterisation the TimePix chip sets and will use this expertise during the project.

4.1.3 Glasgow X-ray characterisation and irradiation facility

The Glasgow laboratory has a range of X-ray sources to allows initial device characterisation. In addition, we have two X-ray tubes at our X-ray facility. The high power X-ray tube allows the generation of monochromatic fluorescence X-rays from various targets to better understand gain and charge collection. This tube is also routinely used to irradiate novel detectors to study their performance after Total Ionising Dose (TID) irradiations - a major degradation mode for ASICs. The second X-ray tube with micro focus allows spacial resolution studies of pixellated detectors.

4.1.4 Diamond Light Source synchrotron

The Glasgow group has an excellent track record of successful applications for beam time at Diamond Light Source - a world leading synchrotron facility. Having access to a monochromatic 2 μm FWHM X-ray beam allows for unparalleled precision in small pixel response mapping. We plan to apply for beam time to map new TI-LGAD TimePix4 detector response to better understand fill factor, improve our fabrication simulation model and adjust pixel designs for future development.

4.1.5 High energy charged particle test beam

The Glasgow group routinely participates in charged particles test beams at CERN and DESY. As part of this work, we will be able to tap into an existing telescope infrastructure for the ultimate novel TI-LGAD detector characterisation. We shall be able to characterise those new detectors for spacial and timing resolution, optimise operation conditions and find limitations of the technology after irradiation.

4.1.6 Irradiation

The devices will be characterised after irradiation. The in-house X-ray source will be used to provide a calibrated ionizing dose. The proton irradiation facility at Birmingham University, UK, will be used for Non-Ionizing radiation (NIEL) fluence exposure.

5 Work plan and deliverables

The work plan outlined here complements work being carried out by the applicants to develop the prototype TimePix4 detectors for the Low-Q^2 tracker.

The start of the project will consist of the characterisation of TimePix3 based TI-LGAD modules using the existing first set of TI-LGAD wafers fabricated at Micron Semiconductor Ltd. This will follow on from the wafer level electrical characterisation of the wafers that is will take place before the project commences. Results from the electrical characterisation will guide the design and order of a second TI-LGAD wafer fabrication run at Micron Semiconductor Ltd including TimePix4 compatible devices.

The deliverables and schedule for the proposed work plan in the first year are given in Tables 1, 2 and 3 with a summary of the plans for continuation into future years outlined in Table 4.

Test prototype TI-LGAD sensor	
Month 0-3	Diode Gain and Timing Characterisation
Month 1-2	Post processing and flip-chip Bonding
Month 3-5	Laboratory Testing of TimePix3 modules
Month 4	Irradiation of sensors
Month 5-7	Beam tests of TimePix3 modules

Table 1: Deliverable schedule for characterising existing TI-LGAD sensors

Fabricate & Test EIC specific TI-LGAD sensors	
Month 0-1	Mask Design
Month 2-6	Wafer fabrication at Micron
Month 6-7	Trenching
Month 7-8	Wafer level electrical testing
Month 8-9	Post processing and flip-chip Bonding
Month 9-12	Laboratory Testing of TimePix4 modules

Table 2: Deliverable schedule for TimePix4 TI-LGADs

Recommend suitability of TI-LGAD for EIC detector sub-systems	
Month 0-4	Include TI-LGAD sensor response in ePIC simulation stack
Month 4-8	Compare simulations using baseline and TI-LGAD subsystems

Table 3: Deliverable schedule for suitability

The Glasgow University research staff due to manage and execute the work plan have secure funding for the duration of the proposed project.

Future work	
Year 2	Beam tests of TimePix4 telescope
Year 3	Bond and test next-gen timing ASIC

Table 4: Proposed schedule for continuation of project in future years

6 Budget

Funding is being requested to fabricate 12 wafers at Micron Semiconductor Ltd, with the trenches etched at the Scottish Microelectronics Center and 6 wafers will be post-processed and 20 devices flip-chip bonded to ASICs at Advacam, Finland. The 12 wafers will allow a range of gain multiplication doses to be used to increase the probability of obtaining a device with high gain and a high breakdown voltage.

The travel costs include travel to a CERN testbeam and the Diamond Light Source. To keep costs down the CERN hostel is assumed and it is is assumed that the Diamond Light Source will cover the costs of two people for 1 week each as is normal for a successful beam time at the Diamond Light Source. No access cost for CERN and the Diamond Light Source are included as these facilities are offered free for the user after a successful bid for beamtime. Access to the Birmingham proton irradiation facility is costed, however no cost for TID irradiation is included as this will be performed in Glasgow.

A request for a SPIDR4 readout system and associated custom TimePix4 PCBs is made. This will be required above and beyond what is existent in Glasgow and based on 20 TI-LGAD modules being assembled. All costs include VAT were appropriate and the exchange rate from www.xe.com on the 14th of July 2023 is used.

6.1 FY24 Funding Request

Item	Cost ($)
Fabrication	64000
Flip-chip	27500
Proton Irradiation	7500
Travel	8000
Consumables	5000
Equipment	10000
TimePix4 ASICS x 20	16000
TimePix4 PCB x 20	9500
SPIDR4 - TimePix4 readout	9500

Table 5: Breakdown of the funding request

The total request is $157000

6.2 Reduced Funding Request

With 80% funding we would fabricate only 8 wafers instead of 12. This will reduce the number of gain multiplication implant doses fabricated and tested. As a result the risk of low gain devices or devices that have insufficient breakdown voltages increases and the probability of a low or zero number of good wafers increases. We will also only post-process 3 wafers instead of 6.
With 60% funding we will only fabricate 6 wafers instead of 12 and only post-process 3 wafers instead of 6. This increases still further the risk of no good devices. The testbeam and proton irradiation part of the program will be cut and only laboratory based tests will be performed on device un-irradiated and irradiated with X-rays.

7 Plans Beyond FY24

The TimePix collaboration is in the process of designing the next generation of ASIC (VeloPix2), focused on the LHCb VELO upgrade 2. The planned specification of this ASIC are ideal for detector upgrades, it will utilize 28 nm CMOS technology to deliver a pixel pitch of 55 μm or less with 20 ps digitisation, data reduction via on chip clustering and vetoing, and through-silicon-vias (TSV) in the matrix of the chip to minimise power drops in the chip which will lead to greater pixel to pixel uniformity. The ASIC will be designed to be radiation hard for a target dose between 3 and 20 MGy. As chip will be designed to meet the LHCb 20 ps timing resolution requirements it will match the LGAD sensor timing resolution and satisfy the requirements for the EIC in-bunch vertex separation as well as fulfilling requirements to be designed to be radiation hard. The ASIC is expected to be ready in time for 2033 which could make it viable for an ePIC detector upgrade/second experimental detector. Small 64x64 pixel prototype ASICs (PicoPix) will be made within the next two years and so testing this bonded to the TI-LGADs forms part of the continuation funding.

Alongside the production of the TI-LGADs for TimePix4 scale devices some additional small 64x64 pixel arrays will be fabricated during this project for testing coupled to the PicoPix prototype ASIC. This next generation timing pixel ASICs is the frist small pitch pixel ASIC with a design time resolution matched to the timing resolution of the LGAD sensors and will realise for the first time a $O50$ μm pitched pixel array with 20 ps timing resolution.

8 Diversity, Equality and Inclusion

The University of Glasgow subscribes to a detailed Equality and Diversity Policy [17] by which the participants of this proposal will act. Any recruitment of students or staff to support this work will adhere to the policies, qualified members of groups underrepresented in this field will be sought out and encouraged to apply.

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