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Referee report on Phd Thesis of Fasih Zareef titled "Characterization of novel semiconductor structures for tracking detectors in high-energy physics experiments using TCT method"

Phd thesis of M.Sc Fasih Zareef entitled "Characterization of novel semiconductor structures for tracking detectors in high-energy experiments using TCT methods" describes the results of tests performed on various Low Gain Avalanched Detectors (LGAD). LGADs currently attract lot of attention in the semiconductor detector community due to their superior time resolution, signal application features, and radiation hardness, which are of great interest for future experiments in Particle Physics at the LHC, EIC, FAIR, to name just a few examples. They are also promising for X-ray imaging applications in medicine or material science.

The thesis describes experiments and presents results characterizing the performance of three novel types of LGADs: i) with an ultra-thin gain layer (20-30 μm) produced at Brokhaven National Lab (BNL) for future experiments at EIC (ii) trench isolated TI-LGAD's investigated in the framework of PixelLGAD collaboration and (iii) double sided 3D column detectors for timing applications produced by Centro Nacional de Microelectronica in Barcelona (CNM). These studies are complemented by investigation of radiation damage effects on BNL and standard LGADs with 50 μm gain layer produced by Hamamatsu (HPK) and by CNM, using proton and neutron beams. The work has been performed by the author in various laboratories, involving the dedicated set-up at AGH, utilizing the Transient Current Technique (TCT) in a broad international collaboration with experts from CERN, BNL, CNM, Universities of Glasgow, Edinburg, Manchester. For the TCT measurements laser beams available at AGH and ELI in Prague were used. Thanks to its excellent focus of the beam (~1.7 μm), the latter facility allowed for a precise characterization of TI-LGAD regarding the electrical isolation of pixels by trenches as a function of depth using the Two-Photon Absorption (TPA-TCT) method.

According to my assessment, the following achievements of the work described in the thesis should be highlighted:

- A detailed comparison of radiation damage induced by proton and neutron beams, showing larger effects for protons when normalized to 1

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MeV neutrons. These effects are quantified through the characteristics of leakage current, detector capacitance after full depletion and bias voltage dependent gain as a function of fluence (ranging from 4 $*10^{14}$ – 10^{15} n_{eq}/cm^2) . From the measured characteristics, the acceptor removal constant has been derived for two vendors HPK and CNN, demonstrating better resilience for the former.

- An in depth characterization of the TI-LGAD performance, focusing particularly on: the effect of trench and doping concentrations on the charge coupling to the pixels as function of charge carries creation, interpad distance (IPD), fill factor and charge transport in the sensor. In particular the depth-resolved TPA-TCT results on IPD are impressive, providing a detailed dependence as a function of the depth of charge carrier creation. The lowest achieved IPD of 5-7 μm demonstrates a superior resolution as compared to the standard LGADs (50-70 μm).
- Quantification of BNL LGADs resilience on proton radiation at fluences 10^{13} -10^{14} n_{eq}/cm^2 (expected at EIC) in terms of breakdown voltage, leakage current increase, and gain reduction. The latter was measured to be 50% and 70% for the respective fluence limits. The acceptor removal coefficient and time resolution was measured. The time resolution was shown to increase from 50 ps to 120-180 ps depending on thickness of the gain layer (20 and 30 μm, respectively)
- Preliminary results on novel 3D double sided column detectors with aspect ratio of 25 from CNM production batch. These results compare leakage current vs Voltage characteristics, charge collection and time resolution across two different pixel geometries (hexagonal and square)

The measurements, data analysis process, and results are clearly described in the thesis, demonstrating a very solid understanding of the subject matter by the author. There are a few minor shortcomings in the descriptions, which I address in the detailed report below. Overall, the results present a valuable contribution to the understanding of novel Low Gain Avalanche Detector (LGAD) sensor technologies, which are of significant importance for future applications in high-energy physics (HEP) and related fields. Some of these findings have already been published: the results on TI-LGADs appear in two JINST articles (one published, the second currently under review), while the findings regarding radiation damage induced by proton and neutron beams are published in another JINST paper, complemented by two conference proceedings. Furthermore, the author has presented these results at five international conferences.

The thesis is structured into an introduction, 6 chapters, a summary, and a conclusion. The core results of the research are presented in Chapters 2, 3, 4, 5, and 6, which are evaluated in greater detail below.

Chapter 1 provides a condensed introduction to the physics of semiconductor detectors, covering charged particle and photon ionization in materials, signal formation in silicon diodes, process induced by radiation damage, the definition of neutron equivalent fluence and annealing. The configurations of PIN and

LGAD structures are introduced, including those specifically evaluated in this work (like standard reference PIN, thin LGADs, TI-LGAD, and 3D LGAD).

Chapter 2 introduces the experimental techniques applied for the electrical characterization of LGADs, namely current-voltage ((I/V) and capacitance-voltage (C/V) measurements, and describes the properties of the laser beam at ELI as well as at the TCT setup at AGH. In this description, I missed details regarding the spatial resolution of the Two-Photon Absorption (TPA-TCT) system achieved at ELI (Section 2.2.4), which is highly relevant for the depth-dependent measurements presented later in Section 5.5. Furthermore, a description of the laser calibration process is lacking, specifically concerning how the laser intensity relates to the number of charge carriers produced by Minimum Ionizing Particles (MIPs). For instance, in Section 4.5.1, it is stated that the laser intensity was kept at a level to produce a charge equivalent to 2 MIPs, but how this was experimentally ensured is not explained. In this context, it would also be worthwhile to require the author to clarify the fundamental physics behind the charge generation, explicitly explaining why the average energy required for electron-hole pair creation in silicon by X-rays/MIPs is approximately 3.6 eV, whereas for a single-photon laser absorption, it corresponds to the silicon bandgap energy of around 1.12 eV.

Chapter 3 describes studies of radiation damage induced by 24 geV/c protons from the CERN-SPS and neutrons from the TRIGA Mark II reactor in Ljubljana on LGADs produced by HPK and CNM, featuring a gain layer thickness of approximately 50 μm. Transient Current Technique (TCT) measurements in the CERN SSD laboratory, utilizing a 1060 nm light, were applied to extract the current-voltage (I/V), capacitance-voltage (C/V), and gain characteristics. The experimental results show a clear degradation of the gain layer, which is more pronounced for protons than for neutrons when normalized to the 1 MeV equivalent neutron fluence. Upon reading this section, a question arises as to whether the specific energy distribution of the neutrons from the reactor should be explicitly considered in this comparison.

The final outcome of this analysis is the extraction of the acceptor removal constant (Table 3-3, Fig. 3.9) for both neutrons and protons across the sensors from the two vendors. The latter demonstrates better performance for the HPK LGADs, as indicated by their smaller coefficients. It would be interesting to include a more detailed discussion of the underlying physical reasons, as the thesis currently provides only a qualitative statement attributing this difference to the doping profile. Furthermore, the author states that LGADs exhibit improved radiation resilience when carbon is co-implemented into the gain layer; however, no quantitative assessment is provided. While this effect might be visible in Figure 3.10, its caption and the accompanying explanation in the text were insufficient to make it fully understandable.

Chapter 4 presents the results of studies of radiation damage in ultra-thin 20 μm and 30 μm LGADs from BNL, which are considered for the EIC. These devices were irradiated by 58.5 MeV protons at IFJ-PAN cyclotron and subsequently investigated using TCT set-up at AGH. Their main characteristics, namely I/V,C/V, gain-versus were extracted before and after irradiation. Before

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irradiation both samples exhibited low leakage currents and I/V characteristics with a broad operation window terminated by breakdown voltage of 80 and 120 V, respectively (Fig.4.4-comment : question how many LGADS were measured?). C/V characteristics shows smaller end capacitances for thicker gain layers (Comment: the sentences on page 89." As the depletion with is inversely proportional to the depletion width, higher capacitance is.." requires reformulation). The gain characteristics was measured with a reference PIN diode and show gains about 20-25 (Fig.4.10). Following irradiation (up to fluences 10^{14} n_{eq}/ cm^2), the devices still display a broad operation window in their I/V, albeit with increased leakage current, a shifted breakdown voltage and a reduced gain. Specifically, a gain reduction of up to 70% at the maximum fluence and 50% at 10^{13} n_{eq}/ cm^2 (expected at EIC)-Fig.4.13 is reported. From the comparison of the gain characteristics measured before and after irradiation the acceptor removal coefficient was determined to be $c=(7.4\pm2.2)*10^{-16}$ cm^2 . This is comparable to the values for thicker LGADs, though it is accompanied by larger errors (Fig.4.14). These measurements are complemented by the determination of time resolutions as a function of constant fraction of the discrimination - CFD (fig 4.17), reaching 50 ps at 70% CFD. The author states that this time resolution can be improved by "a faster timing boards". One can therefore conclude that this resolution includes contribution from the signal processing, which unfortunately remains unquantified. Furthermore, the time resolution quickly deteriorate as a function of fluence, much faster for the sensor with thicker gain layer reaching 180 ps and it remains an open question if the measured gain and time losses are acceptable for EIC experiments.

Another interesting aspect presented in this chapter is the investigation of gain characteristics as a function of laser intensity, which directly relates to the density of charge carriers in the sensor (Figs. 4.11–4.12). In my opinion, these results would be scientifically more sound if they were quantified in terms of actual charge density rather than the arbitrary "DAC" which is somehow related to the physical figure of merit (see my previous remark on laser calibration)

Chapter 5 presents the results of an investigation into trench-isolated LGADs (TI-LGADs), which were developed for position-sensitive sensors with a pad readout, aiming to minimize dead zones in charge collection caused by the trench structure. The TI-LGADs were fabricated by Micron Semiconductor Ltd., featuring trenches with a width of approximately 2 μm and a depth extension of 7 μm filled with silicon oxide (Fig. 5.2). This processing was carried out by the Scottish Microelectronics Centre, ensuring no gap between the trench and the gain layer. Four different wafers were produced—all 200 μm thick—but with slightly different boron doping concentrations and five distinct pad layouts. Among these, the layout featuring two pixels separated by a trench (Layout E) was the primary subject of this investigation. The author also conducted simulations using Synopsys Sentaurus TCAD software.

Electrical characterization was performed utilizing the TCT setups at AGH and ELI in Prague, employing the Two-Photon Absorption (TPA-TCT) method to conduct scans as a function of depth. The current-voltage (I/V) characteristics exhibit an extended operation window with a width of up to 900 V and leakage

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currents around 10-100 nA/mm^2, which are highest for the Layout E sensors. Figure 5.7 shows the I/V curves for several samples of Layout E sensors and reveals large variations in leakage current between individual samples. This dispersion is left uncommented in the text, and it would be interesting to understand the physical reasons behind this behavior. The capacitance-voltage (C/V) characteristics are well-reproduced by the simulations, and the sensor gain is found to be around 2–3.

The most interesting results concern the Interpad Distance (IPD) and charge coupling between pixels in Layout E sensors, as detailed in Section 5.4.3. Figures 5.15 and 5.18 display the IPD versus voltage, demonstrating an excellent pixel separation by front illumination of approximately 2-10 µm , depending on the laser wavelength used : namely 1060 nm infrared and 660 nm red. By the back illumination at ELI with 800 and 400 nm worse IPD resolutions ranging from 7-22 µm were achieved. The choice of wavelength and illumination direction determines the initial spatial distribution of the generated charge carriers and, consequently, their drift transport. The TCAD simulations show better agreement with the short-wavelength laser results, which the author explains by the laser beam spot size not being fully accounted for in the simulation model.

Furthermore, the detailed studies on charge separation between pixels as a function of the beam incident position on the sensor are impressive, precisely demonstrating the charge sharing mechanism between pixels (Figs. 5.16 and 5.17). Particularly rich in information are the results obtained via TPA-TCT at ELI, which allowed the author to establish a detailed dependence of the IPD on depth (Figs. 5.20 and 5.21) in relation to the boron concentration in the gain layer and the direction of illumination (front versus back side). The latter clearly demonstrates the critical role of lateral diffusion on the IPD when the ionization point is deep inside the sensor, which leads to an increased effective IPD and a consequently degradation of the fill factor. The detailed signal characteristics (signal rise time, duration, and normalized charge) extracted from these depth scans are presented in Figures 5.22 and 5.23; together with the aforementioned results, they constitute a true highlight of this thesis.

Finally, the chapter presents an attempt to optimize IPD values by improving the trench filling process. However, due to the early breakdown of LGADs in the second fabrication batch, it was only possible to perform experimental characterization prior to reaching full depletion. The reason for the break-down was found and attributed to trench.

The final part of the thesis, Chapter 6, presents preliminary results on a novel 3D double-sided column detector with hexagonal and rectangular pixel geometries for timing applications. Findings show that current-voltage I/V curves differ from typical LGAD behavior, exhibiting a very narrow operational voltage window and rapidly increasing leakage current, with only 55% of rectangular and 70% of hexagonal structures passing 10 µA. current compliance. Transient Current Technique (TCT) analysis, performed using the AGH setup after removing back-side metal and leaving a thin titanium (Ti) layer, evaluated charge collection for both geometries under front and back

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illumination and show larger charge signals for hexagonal geometry but less uniform Time of Arrival distributions as a function of light incidence position (Fi 6.12 and Fig 6.16). They are quantified as so called Median Absolute Deviation on Fig 6.14 and 6.17, which unfortunately lacks definition.

In summary presented work described very extensive experimental work conducted at various laboratories with a rich, interesting and original outcome contributing to the very rapidly advancing field of LGAD detectors. The results were obtained utilizing modern and advanced TCA techniques and were achieved in close collaboration with LGAD vendors. The results are discussed and interpreted by the author in clear way, proving his deep understanding of theoretical and experiment aspects. Shortcoming in the presentation or discussions of results, pointed in this report, do not alter my very good assessment of this work. I evaluate it as completely sufficient of in view of criteria defined for phd thesis (Ustawa Prawo o Szkolnictwie Wyzszym I Nauce z 20.07.2018 (dz.. U. 2018 poz 1668 z pozn, zm)) and suggest further proceedings by the Faculty.

Podsumowując stwierdzam, iż przedstawiona do recenzji praca mgr. Fasiha Zareefa zawiera bardzo wartościowe wyniki, uzyskane po raz pierwszy i wnoszące istotny wkład do dyscypliny. Praca spełnia warunki ustawy o stopniach naukowych i tytule naukowym doktora wymienione w Ustawie Prawo o Szkolnictwie Wyższym i Nauce z 20.07.2018 (Dz. U. 2018 poz. 1668 z pozn. zm) , w szczególności art. 87.1 oraz 187.2 i potwierdzam że praca zawiera orgynilane rozwiązanie problemu naukowego i wnoszę do Rady Dyscypliny Nauk Fizycznych AGH o dopuszczenie Pana Nory mgr. Fasiha Zareefa do dalszych etapów przewodu doktorskiego.

Z poważaniem

Piotr Salabura

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Elektronicznie podpisany przez Piotr Salabura
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