Institution: University of Liverpool

Unit of Assessment: 9 – Physics

Title of case study: N-in-P radiation-hard sensors for the Large Hadron Collider (LHC)

1. Summary of the impact (indicative maximum 100 words)

Radiation hardness is key for sensors used in many nuclear medicine, space and defence applications, and for nuclear reactor monitoring and fuel handling. It is vital to academic research in the high particle fluence environments found in particle and nuclear physics. At Liverpool, the development of novel radiation-hard silicon sensor technologies was driven by sensor requirements at the LHC. This research has led to the adoption of n-implant in p-type planar silicon (n-in-p) sensors in the wider research community and by commercial suppliers of sensing devices including Micron Semiconductor and e2v (UK), Hamamatsu Photonics (Japan), CNM (Spain) and FBK (Italy).

2. Underpinning research (indicative maximum 500 words)

Researchers at Liverpool were among the first to propose n-dopant implanted read-out to achieve greater radiation hardness in high-resistivity silicon strip detectors. Through the PhD thesis project of a CASE student (Moshe Hanlon, 1999) with Micron Semiconductor (UK) Ltd, we explored the possibility of producing such sensors with single-sided processing by starting with a p-type substrate (up to this point the detectors provided to nuclear physics, particle physics, space science, astrophysics and medical physics had been based on very high resistivity n-type silicon substrates). Full-size (10 cm × 10 cm) detectors were designed at Liverpool and produced in this n-in-p technology with Micron, e2V and Hamamatsu. Detailed characterisation work on post-irradiation performance was led by Liverpool internationally resulting in 30 Liverpool journal publications in this area.

The international success of the Liverpool group in detector development has depended on the unique facilities of the (STFC funded) Liverpool Semiconductor Detector Centre. Through this, we have continued to play a leading role in the development of these technologies with refinement of the p-type structures and deeper understanding of the fundamental device physics that explains the post-irradiation properties. As part of our recognition for developing this technology, one of our team members, Dr Gianluigi Casse, currently leads the RD50 collaboration at CERN (Radiation Hard Sensors for the LHC) of over 300 scientists, while another, Professor Phil Allport, is Upgrade Coordinator of the 3000 strong ATLAS Experiment on the LHC.

This research has led the two main LHC experiments, ATLAS and CMS (the world's largest scientific experiments), to adopt n-in-p as their baseline technology for the major (~£200M component costs) tracker upgrade programmes required for the HL-LHC. The Liverpool group also built the first 40 full size LHC n-in-p modules for the international ATLAS tracker upgrade prototyping programme and, in 2012, completed the build of an entire n-in-p Vertex Detector for another LHC experiment, LHCb, the first complete detector system of its kind in the world.

3. References to the research (indicative maximum of six references)

1. P.P. Allport, "Silicon strip detector designs for the ATLAS experiment." Nucl. Instrum. Meth. A386 (1997) 109-116. DOI: 10.1016/S0168-9002(96)01103-5
2. G. Casse et al. "First results on charge collection efficiency of heavily irradiated microstrip sensors fabricated on oxygenated p-type silicon" Nucl. Instrum. Meth. A518 (2003) 340-342. DOI: 10.1016/j.nima.2003.11.015
3. G. Casse, "Radiation hardness of p-type silicon detectors." Nucl. Instrum. Meth. A612 (2010) 464-469. DOI: 10.1016/j.nima.2009.08.050
4. A Affolder et al. "Charge collection efficiency measurements of heavily irradiated segmented n-in-p and p-in-n silicon detectors for use at the super-LHC", IEEE Trans. Nucl. Sci. 56, 765-770 (2009). DOI: 10.1109/TNS.2009.2012856

5. G. Casse et al. "Study of the response to minimum ionising particles of microstrip detectors made with float zone and magnetic Czochralski silicon after neutron irradiation", Nucl. Instrum. Meth. **A598**, 671-674 (2009). 10.1016/j.nima.2008.09.048
6. G. Casse et al. "Comparison of charge collection efficiency of segmented silicon detectors made with FZ and MCz p-type silicon substrates", Nucl. Instrum. Meth. A591 (2008) 178-180. DOI: 10.1016/j.nima.2008.03.090

Research funding:
1. Research funded through The University of Liverpool, Department of Physics Particle Physics Rolling Grant, STFC, ST/F007469/1, End 9/12, (£5,357,268), PI: P. Allport
2. Junction engineering of microstrip silicon sensors to operate in controlled charge multiplication mode for enhanced radiation tolerance , STFC, ST/H003924/1, End 6/14, (£75,256), PI: G. Casse

4. Details of the impact (indicative maximum 750 words)

Silicon Providers

Liverpool's contribution to developing and modelling the intrinsic devices has made them a cheap, stable and reliable commercial technology. Typical costs are less than 20% more than those for non-radiation-hard devices. The number of international companies and research facilities now able to offer p-type sensors for high radiation environments has grown to 8, including the world's largest supplier Hamamatsu Photonics (Japan) and now 2 UK companies (Micron and e2v Technologies Ltd). From 2008 onwards, this research was continued as part of the Liverpool STFC Rolling Grant.

Suppliers such as Micron Semiconductor Ltd (MSL) and e2v supply to many markets from medical applications to space and defence, but often the new product lines are first developed to meet the exacting requirements of fields such as particle physics. This has been particularly true for MSL, where the company Director writes in his supporting letter that their collaboration with Liverpool *"…has proven and continues to be, of great benefit to expanding commercial activities, particularly in Asia…*" On radiation-hard developments such as n-in-p, introduction of interstitial oxygen, and guard-ring optimisation for post-irradiation high-voltage operation, he writes: "*Since 2008, the establishment of P-type substrate technology, which has relied on MSL fabrication and process engineers working closely with Liverpool's device expertise, has established MSL's pixel and strip offerings as the most radiation-tolerant in the world. These devices represent more than 30% of MSL's business, and the technological edge over competitors permits bids and results in major contracts, both in the UK and worldwide*". MSL has an annual turnover in excess of $5 million and "…*is the UK's leading radiation sensor specialist and provides a wide range of products for applications in scientific laboratories, the nuclear industry and aerospace and defence applications, and is a qualified supplier for ESA and NASA to both H- and K-level standards*."

In addition, Liverpool has contributed to designs available from other international companies (Hamamatsu Photonics, and CNM) who now provide p-type sensors as part of their catalogue. With CNM, we also provide the mask designs for the different prototype devices developed for studies of performance after extreme neutron and proton irradiation.

We helped e2v develop this technology with Liverpool mask designs through a joint industry-academia grant (ST/F011571/1 with £327k to Liverpool) leading a joint publication with e2v. We have also held CASE studentships with e2v and Hamamatsu (UK) as well as with MSL.

In the case of MSL (supplying mostly to the nuclear industry, space and defence) their chief detector designer, Dr. Susanne Walsh, was trained in the use of the CAD packages needed for sensor mask layout during an 8 month placement at Liverpool and continues to work closely with our design experts. Dr Walsh does all the company's in-house sensor design.

Other Impact

The building of the LHCb n-in-p VELO 2008-2012 was done based on the n-in-p research, but required electronics expertise across a broad range of UK industry including Hawk Electronics and Stevenage Circuits. The technologies developed that were ancillary to the n-in-p sensors, but nonetheless vital to completing the instrumentation, included the precision, low-thermal impact component mounting by Hawk Electronics, who won a NW Industry award for their work with Liverpool in 2008 and the circuit layout and design by Liverpool of high-tech hybrids (that hold the sensors) by Stevenage Circuits. On the back of this research, Hawk has now been enabled to bid for EC contracts and Stevenage Circuits has added thermal management to part of its product range of hybrids. Both are involved heavily in the ATLAS tracker upgrade prototyping efforts for the HL-LHC at Liverpool with the prospect for bidding for major future contracts.

The detectors designed by Liverpool for the LHC now form the basis of a major new initiative in proton therapy instrumentation which recently received a £1.6 million Translation Award from the Wellcome Trust. Here, radiation hardness is key to long-term operation in the proton beam.

5. Sources to corroborate the impact (indicative maximum of 10 references)

1. The Managing Director of Micron Semiconductor has provided a letter of support to corroborate that they have collaborated closely on R&D with Liverpool University for over 20 years and that this relationship continues to be of great benefit to them.
2. The Leader of the Radiation Detectors Group *CSIC* and Technology Area Coordinator at Centro Nacional de Microelectrónica has provided a letter of support to corroborate that their links with Liverpool University and RD50 have led to new products for use in high radiation environments.
3. The Managing Director of Hamamatsu Photonics UK Ltd has provided a letter of support to corroborate the value they attach to their collaboration with Liverpool University.
4. The Director of Hawk Electronics has provided a letter of support to corroborate that their work with Liverpool University helps build and maintain their high-tech skills base.