Training network for the development and application of DMAPS

Univ. of Birmingham, Univ. of Bristol, Univ. of Glasgow, Lancaster Univ., Univ. of Liverpool, Univ. of Oxford, Swansea Univ., Univ. College London, STFC-PPD, STFC-TD

This document proposes 10 Industrial Strategy Fund Studentships. The PhD projects have strong links with industrial and other partners and focus on the development of DMAPS devices in HV/HR CMOS technology, in close collaboration with Foundries and international research laboratories and on applications in areas such as hadron and radiotherapy, where new NHS and private facilities are set to open in the UK. A dedicated training programme will be developed for the students.

Research strengths of the institutes

STFC funded university research groups, STFC PPD and STFC TD have a strong international track record in the development of CMOS Monolithic Active Pixel Sensors (MAPS) that offer small pixel size, low noise and low mass and of planar silicon sensors that meet stringent requirements on radiation tolerance and timing. Developed sensors are exploited in particle and nuclear physics to track charged particles and in astronomy for high-granularity photo-detection. Partners on this proposal played leading roles, together with UK industry, in the development of sensors used by LHC experiments and of MAPS technology for particle tracking and scientific imaging.

Alignment to STFC priorities, the industrial strategy and interdisciplinary nature of the project

Silicon sensors, in all their formats, are a strategic and enabling technology. They are used throughout STFC's research areas and played a key role in many discoveries in the last 30 years. Much of STFC's scientific output has only been possible due to these devices, whilst areas beyond STFC's core research priorities have benefitted from sensors developed with support by STFC. Areas that benefitted include particle physics, nuclear physics and astronomy, laser facilities (fluorescent lifetime measurements), neutron science (mass spectroscopy), photon, x-ray and space science (photon and low-energy electron detection), transmission electron microscopy, health applications (radiation monitoring and hadron therapy) as well as other commercial areas.

There is a wide consensus that hybrid sensor technologies will be replaced by Depleted Monolithic Active Pixel Sensors (DMAPS) using commercial HV/HR-CMOS technologies. The latter bringing major improvements in the critical areas of speed, radiation-hardness, timing and cost.

The UK DMAPS consortium project proposes to coordinate the expertise and resources of 11 university research groups, STFC national laboratories and external partners to develop and exploit the sensor technology for STFC's future science programmes and facilities, whilst working with commercial and other partners to realise applications of DMAPS technology in areas where today more traditional silicon is used. A Statement-of-Interest towards funding for the prompt launch of the consortium was submitted to Science Board in February 2017. Whilst this is under consideration, there could be a substantial boost to this area of R&D if the studentships, described hereafter, are funded. It is hoped that in the future a case can be made for more general support for the development of DMAPS applications to the new Industrial Strategy Fund. The proposed studentships will help to demonstrate the breadth of commercial links that already exist.

The interdisciplinary nature of the studentships is illustrated, on the technology side, by the strong participation of companies and other non-academic partners that specialise in advanced micro-electronics, and on the application side, by the involvement of companies and partners in the medical sector, involved with the delivery of radio and hadron therapy for cancer treatment.

The Projects

Project 1: ***Design of radiation-hard CMOS sensors for precision beam profiling and dosimetry for application at new hadron therapy facilities in the UK***. The project complements an existing CASE studentship with NPL and will focus on the new sensor design rather than proof of principle with existing systems. Prototyping of devices designed by STFC Detectors and Electronics Division will benefit from the RD50 HVCMOS development programme to which both RAL and Birmingham contribute. For device fabrication leading to a successful instrument development with NPL, further funding can be sought from the NPL Metrology for Medical Physics Group.

Partners: Univ. of Birmingham (lead), CMOS Sensor Design Group at RAL, NPL, Univ. Hospitals Birmingham NHS Foundation Trust.

Supervisors: Dr. Steve Worm, Dr. Iain Sedgwick, Prof. Phil Allport,

Placement: at RAL, working within the Detectors and Electronics Division, and at NPL.

Project 2: ***Simulation and evaluation of HV-CMOS sensors.*** The student will work on the development of HV-CMOS technology towards high granularity, fast and radiation tolerant DMAPS

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devices. Working with the supervisors in Liverpool and PPD, they will carry out device simulations of structures for the planned RD50 submission to LFoundry Srl. The student will also evaluate existing and new prototype devices. Submissions, coordinated by Liverpool, are funded collaboratively through RD50.
Partners: Univ. of Liverpool (lead), STFC-PPD, FBK-CMM Trento, LFoundry Srl.
Supervisors: Dr. Eva Vilella, Dr. Jens Dopke
Placement: 6 months with FBK-CMM. A further placement with LFoundry Srl. is to be confirmed.

Project 3: *Development of an accurate, MAPS based, dosimetry system for MR-linacs*. MR-linacs combine simultaneous Intensity Modulated Radio Therapy with MRI, requiring precise beam monitoring in the high magnetic field area inside the MRI bore. The student will design and build a MAPS based beam monitoring system covering the full beam entry area, and develop the DAQ, firmware and data analysis software to test the sensors. Access to IMRT machines (Swansea), an MRI machine (Bristol) and an MR-linac (Netherlands Cancer Institute) will be provided free of charge.
Partners: Univ. of Bristol (lead), Swansea Univ., Netherlands Cancer Institute, vivaMOS Ltd
Supervisors: Dr Velthuis, Dr Hugtenburg
Placement: 6 months at vivaMOS Ltd. to learn about MAPS and develop the system firmware

Project 4: *Dosimetry using a MAPS system in MR-linacs*. The student will work on the software to verify the dose, for the new instrument (see project 3). MRI yields the exact tumour position, but is also used to determine the patient position in order to verify radiation transmission through the patient, placing tight constraints on acceptable geometric distortions. Building on current research at Swansea University, information about the radiation characteristics of tissue needs to be determined by mapping the MR signal to atomic composition of tissue.
Partners: Swansea Univ. (lead), Univ. of Bristol, Netherlands Cancer Institute, vivaMOS Ltd
Supervisors: Dr Hugtenburg, Dr Velthuis
Placement: 6 months at the Netherlands Cancer Institute to work with their dosimetry experts

Project 5: *Application of high resolution HV-CMOS DMAPS in a 3D water phantom*. The student will test an existing 1D water phantom and simulate beam interactions with the water target and sensors. They will work on simulations and commissioning of the new 3D phantom. Field tests are expected in the second year and towards the end of the PhD the student will work to refine the data analysis to speed up the use of the phantom for therapy planning. This is the first time such detectors are used commercially to provide clinics with better modelling and calibration of treatment beams and thereby greater accuracy and safety for patients. The studentship is embedded in a £750k project, carried out by Liverpool, funded by PPI Ltd.
Partners: University of Liverpool (lead), Proton Partners International Ltd.
Supervisors: Prof. Gianluigi Casse, Dr Ian Barwick
Placement: the student will have access to PPI Ltd. accelerator test facilities for their research and undertake a 6 month placement at one of these facilities.

Project 6: *Evaluation of TowerJazz DMAPS and development of large area modules*. MALTE, a MAPS sensor designed in the TowerJazz 180 nm technology, is fast, radiation hard and achieves high granularity. The read-out of the chip is fully asynchronous lowering power consumption. The student will evaluate different pixel architectures, determine the radiation hardness of the devices, and develop large area modules and multichip testing.
Partners: Unive. of Oxford (lead), CERN, TowerJazz
Supervisors: Prof. Daniela Bortoletto, Prof. Ian Shipsey
Placement: 3 months a year at CERN working with the designers of MALTE to conduct irradiation studies, and evaluate performance in test beams.

Project 7: *Fast Treatment Verification for Spot scanning Proton Therapy*. For fast QA at new NHS proton therapy facilities, the combined measurement of beam profile and energy with fast turnaround is essential. A full 2D profile requires a low mass fast radiation-hard pixelated detector linked with scintillators offering excellent energy resolution at the energies relevant to proton therapy. UCL have demonstrated 0.5% energy resolution for 60 MeV protons. Proof of principle of a combined system will initially be demonstrated with existing silicon strip tracking systems, before a full instrument based on radiation-hard DMAPS will be developed.
Partners: UCL (lead), Univ. of Birmingham, Univ. Hospitals Birmingham NHS Foundation Trust.
Supervisors: Dr. Simon Jolly, Dr. Tony Price
Placement: Prototype testing at the Christie Hospital Proton Therapy Research Beamline

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Project 8: *Optimisation of CMOS processes for sensor applications by post-processing.* To achieve satisfactory signal charge, CMOS sensors are usually produced on high-resistivity substrates, excluding some interesting CMOS processes and adding cost. The student will explore the optimisation of signal charge by post-processing options (thermal treatment, pre-irradiation) using test ASICs on standard substrates in different CMOS processes in close cooperation with the partners and the CMOS Foundries, e.g. ams AG and LFoundry Srl.
Partners: Lancaster Univ. (lead), STFC PPD, KIT-ASIC and Detector Laboratory
Supervisors: Dr. Daniel Muenstermann, Dr. Harald Fox, Dr. Jens Dopke
Placement: at KIT-ADL to work on test circuit design. A further placement at a foundry is envisaged.
Project 9: *Application of HV-CMOS sensors in precision mass spectrometry.* Fast and precise mass spectrometry has applications in the detection of explosives and narcotics, in medical diagnostics and in process control in industry and agriculture. The student will develop and evaluate an in-vacuum DMAPS system for the detection of ions. The partners will support the project through co-supervision, consultancy and the loan of ion source equipment.
Partners: University of Liverpool: Department of Physics (lead) and Department of Electronics & Electrical Engineering, Q-Technologies Ltd.
Supervisors: Dr. Joost Vossebeld, Dr. Steve Taylor
Placement: 6 months with Q-Technologies Ltd., during which the student will work on the development and deployment of compact mass spectrometry for a range of applications.
Project 10: *Characterisation of sensors to evaluate the performance of the front-end electronics before and after irradiation by X-rays and protons*. Using Glasgow's X-ray source, the performance of the front-end can be calibrated and compared to design values providing feedback for future designs. The student will also evaluate the tracking performance of the sensors using radioactive sources and test-beams. They will work on developing FPGA based readout systems for the sensors and integrate them into the various test systems.
Partners: University of Glasgow (lead), CERN
Supervisors: Prof. Craig Buttar, Dr. Heinz Pernegger
Placement: 6 months at CERN

Identifying the Candidates

The proposed studentships are spread over a substantial number of institutes with, in most cases, only one studentship to fill. Having recently completed the process for appointing the new PhD students for October 2017, several institutes still have suitable candidates on their books. Where necessary we also benefit from a strong international R&D network to advertise R&D related PhD positions efficiently to a wide audience. Most studentships can be taken up by students with either a degree in either Physics or in Electronical Engineering.

A Multi-Institute Training Network on CMOS imaging and tracking detectors

The institutes, with input also from the partners, undertake to deliver a UK wide training programme tailored to the needs of students working on CMOS sensor technology and some of the key areas where it is applied. The training network will remain in place beyond the proposed studentships, and will be open to students in the participating research groups working on CMOS related PhD projects. This brings substantial benefits as individual research groups have in general too few students in this area to warrant developing such a broad range of training material locally. The training will build on courses already offered at institutes, or collaboratively by existing networks of Universities, to which students will participate in person or using video conferencing. New more advanced courses will be added. Students can follow a tailored training programme that will include courses such as: "*Detectors in particle physics", "Imaging sensors for astronomy", "Radiation damage in silicon and mitigation strategies", "Data analysis using PYTHON and ROOT", "DAQ: systems and technologies", "Introduction to communication protocols", "Introduction to scientific and medical accelerators", "Radio and hadron therapy in oncology"*. In addition a summer school on *"CMOS sensors for particle tracking and imaging"* will be established to start in the summer of 2018. The students will also have access to training courses offered through the ERC supported EUROPRACTICE network. EUROPRACTICE currently offers 19 courses varying in duration from 2 to 5 days and covering a range of topics including analogue and digital IC design in different technologies, VHDL communication, and training on different IC verification and simulation tools.
In summary, the unique skills-set that students on this project will build through their training, their research project and the external placements, will make them highly employable in both high-tech industries and in the academic research environment.

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