Institution: University College London
Unit of Assessment: 13 - Electrical and Electronic Engineering, Metallurgy and Materials

a. Overview

UCL's submission to Unit of Assessment 13 comprises staff from its Department of Electronic and Electrical Engineering (EEE), including those holding joint appointments with the London Centre for Nanotechnology (LCN). We collaborate closely with staff returned in Units of Assessments 1, 5, 8, 9, 11, 12 and 15. Some of these collaborations are in topical research groupings drawing staff from several Departments, whilst some are large-scale collaborative Centres, such as the LCN and the UCL Centre for Security and Crime Science. Researchers are affiliated with a Department, a Centre, or both, with increasing use being made of joint appointments. UCL considers that this interdisciplinary approach is vital to solving contemporary research problems. The five Research Groups, listed below, bring together research areas required for the Unit's mission. Heads of Research Groups are underlined and staff with joint EEE-LCN appointments are marked with a '*'. All five Research Groups are covered in the submission.

Communications & Information Systems Group (CISG): Prof. I Darwazeh, Dr. I Andreopoulos, Dr. C Masouros, Dr. J Mitchell, Prof. G Pavlou, Dr. M Rio, Dr. M Rodrigues, Dr. K Wong

Electronic Materials & Devices Group (EMDG): Prof. Sir M Pepper*, Dr. N Curson*, Dr. J Elzerman*, Prof. R Jackman*, Dr. A Kenyon, Dr. H Kurebayashi*, Dr. J Morton*, Dr. I Papakonstantinou, Dr. E Romans*, Dr P Warburton*

Photonics Group (PG): Prof. A Seeds*, Dr. S Day, Dr. A Fernandez, Dr. CP Liu, Prof. H Liu, Dr. N Panoiu, Dr. C Renaud, Dr. D Selviah

Optical Networks Group (ONG): Prof. P Bayvel, Dr. R Killey, Dr. S Savory, Dr. B Thomsen, Dr. P Watts

Sensors Systems & Circuits Group (SSCG): Prof. Brennan, Prof. Demosthenous, Prof. Griffiths, Dr. X Liu, Dr. O Mitrofanov, Dr. K Tong, Prof. K Woodbridge

Each research student or research staff member is assigned to a particular Group, which gives students strong and clear group identity and supports their research. Boundaries between Groups are intentionally porous, with many students and research staff having supervisors from more than one Group as required for the particular research project.

Co-ordination of the Unit's research is through the Departmental Research Committee, comprising the Head of Department (Seeds), the Director of Research (Demosthenous) and Heads of Groups. This committee monitors research and technology transfer performance, oversees departmental provisioning in support of research in terms of infrastructure, space and staffing, and facilitates coordinated responses to research opportunities, in consultation with the Faculty Research Board.

b. Research Strategy

The strategic focus of the Unit's research is on information: information sensing, ranging from nerve impulses to radar returns; information processing from specialised analogue and digital signal processing to systems for "beyond Moore's Law" quantum information processing; information transmission, with new coding approaches, advanced wireless systems and technologies at up to THz frequencies, optical communications systems that will reach the ultimate throughput limits of optical fibre and the exploration of new network and service approaches to enable the future internet; information output from nerve amplifiers to advanced display modelling. Our research spans the range of the subject from fundamental materials investigations through the creation of novel devices and sub-systems to large-scale systems studies. Since energy, manufacturing and public policy considerations underpin all electronic systems and their applications we integrate these considerations in all our work with active participation in the worldwide GreenTouch collaboration for energy efficient Information and Communications Technology (ICT) and participation in UCL Engineering initiatives, such as the recently created Department of Science Technology Engineering and Public Policy (STEaPP). Our work involves extensive industrial and other user collaboration, a noteworthy new initiative in which we are

involved being the BBC Research and Development-UCL strategic partnership, with its new 80 person joint research centre housed at 1 Euston Square.

In our RAE2008 submission we stated our five principal planned themes for research as broadband access systems using fixed and wireless technologies; the creation of advanced interoperable networks; new information processing devices (including quantum devices, to overcome contemporary speed limitations); silicon photonics; sensors of all types and their integration for security and healthcare applications. To implement these themes we have expanded staffing from the RAE2008 submission level of 33 FTE to 38 FTE (all submitted under REF2), making high quality appointments from leading centres in support of our strategy. We have also obtained long-term support for these themes through the award of an RCUK Basic Technology Programme and four EPSRC Programme Grants during the REF period (total value ~£28 million).

We have continued to invest heavily in infrastructure to support our research mission, as detailed in Section d. Our research has led to many scientific achievements in this period. Key achievements and plans by Research Group (see Section a) are detailed below.

CISG: In our RAE2008 submission, key future aims were to focus on 4G/5G wireless systems, the "Future Internet" and to establish an industrially funded lab facility. In the context of 4G/5G technologies we focused on spectrum and energy saving through new signal and system architectures. Spectrum saving by new Spectrally-Efficient Frequency Division Multiplexing (SEFDM) led to the world's first demonstration of SEFDM signals, saving up to 30% of bandwidth [IEEE Trans CAS **59** 1107 (2012)]. This is being applied to the optical domain by research groups worldwide (eg Cork-Ireland and Tsinghua-China). Work in co-operative and multi-hop wireless networks led to the world's first proposal of a beam-forming solution in a cognitive radio environment [IEEE Trans Signal Processing **57** 4871 (2009)] and resulted in new EPSRC funding in collaboration with BT. In the context of the Future Internet, we have led three new flagship European projects: COMET on information-centric networking (ICN), FUSION on service-centric networking and ENVISION on network architecture, resources and content cross-optimisation. We have made scientific breakthroughs in a number of related areas, including showing the flattening of the Internet inter-domain structure [IEEE Trans Networking **18** 164 (2010)] and solving the problem of optimally locating in-network area managers [IEEE Trans Computers **62** 1207 (2013)]. Work on ICN also resulted in new EPSRC funding. Furthermore, wireless sensor network (WSN) research, linking to the Internet-of-Things, derived the first theoretical foundations for energy-neutral WSNs [IEEE Trans Wireless Comms. doi: 10.1109/TWC.2013.092013.121649] and resulted in a UCL-led academic/industrial consortium with new EPSRC funding. Work in these areas resulted in seven new grants led by CISG members, with funding of £4.6 million from EPSRC and the EU.

Concerning creating a new lab facility, our industrial links with Aeroflex resulted in the establishment of a unique laboratory with £1.8 million of equipment for full wireless signal generation and detection including 2G, 3G, 4G and non-standard signal formats.

A key part of our future strategy, supported by UCL Engineering, is to create and lead a new Communications Institute, which will bring together all communications and networking activities across the Unit and other UCL departments, since we recognise that the future communication landscape will require both vertical and horizontal integration across different disciplines. We will also further develop our partnership with CERN, where through the ACEOLE €3.5 million EU funded project, our research has transformed our passive optical network architectures into designs for use in the upgraded High Luminosity Large Hadron Collider to be in place by 2020 [IEEE Trans Nuclear Science **58** 1628 (2011) and IEEE Trans Nuclear Science **61** 386 (2011)]. Finally, we shall maintain our leading role in the EU's Future Internet Assembly (FIA) and continue our work in the design of the future context, content and service-aware Internet through our extensive collaborations with European industrial and academic partners

EMDG: As recorded in the RAE2008 submission the group was one of the founding units of the London Centre for Nanotechnology, LCN. Our 2008 strategy included exploiting the unique interdisciplinary, and inter-departmental environment of the LCN for our work on materials and devices. Key, and distinguishing, elements of our approach are establishing new functionalities based on fundamental considerations extending to actual use in hardware, often in collaboration with industry or other institutions. The LCN brings together different areas of expertise and interest

and develops facilities too expensive for any one area, which are, however, economic as a service for all, such as the 200 m^2 Nanofabrication Facility and extensive cryogenic facilities.

Considerable financial support has been obtained and the Group is involved in three UCL Programme Grants, as well as a number of other Research Council and Industrial grants. Material systems studied include silicon, gallium arsenide, diamond and both silicon and metallic nanoparticles. As an example of our approach we showed that it is possible to couple two quantum systems via a photon link allowing the generation of spin information in a quantum dot to be optically transferred to another dot [Science **320** 772 (2008)]. This will allow the next generation of quantum information devices to inter-communicate via quantum communication links. Achievements include novel electronic properties exhibited by a single unreacted (dangling) bond [Nature Comms **4** 1649 (2013)] and a single impurity atom [Nano 2012] on the surface of silicon. This allows integration with CMOS utilizing the advances in the technology of silicon fabrication, supported by our measurements showing that coherence times of nuclear spins in silicon can exceed 3 minutes [Science **336** 6086 (2012)]. First steps to quantum integrated circuits in silicon are the measurement of a single donor spin using a single electron transistor [Nature **489** 541 (2012)]. New paths to quantum logic are suggested by our finding that the degeneracy of momentum and spin states of electrons in GaAs quantum wires are linked. Superconductor phase slips are being used for an accurate measurement of the electron charge to accompany semiconductor work with this objective. Si-rich nanodevices are being developed for memory and photovoltaic technologies. Semiconducting diamond, including in FETs, has been shown to possess novel properties for high temperature electronics and imaging. Future strategy will build on these utilizing inter-LCN and inter-departmental collaboration, key performance indicators being high quality publications and successful collaborations.

ONG: As described in the RAE2008 submission, the key research themes for ONG were (i) study of fundamental nonlinear quantum and energy limits to the capacity and flexibility of optical networks, (ii) use of novel signal processing techniques to realise network performance approaching these limits, (iii) definitively setting the scene for optical networks of 2020 and beyond, covering different time- and length-scales. We have made immense progress with numerous key achievements. For (i) these include transformational developments in digital signal processing to demonstrate new receiver-based digital signal processing techniques in mitigating linear and nonlinear impairments in a variety of modulation formats most of them for the first time; for example, [Optics Express **16** 804 (2008), IEEE JSTQE **16** 1217 (2010), Optics Express **19** 9296 (2011)]. These techniques have been extended to optical access networks, increasing both subscriber rates and numbers of subscribers by two orders of magnitude [IEEE J Lightwave Tech **31** 609 (2013)]. In (ii), the focus of our work has been the physical understanding of the physics of nonlinearities and the role of electronic processing to enable simultaneous increases in transmission capacity, spectral efficiency and transmission distance. In-house development of powerful analytical and simulation tools has helped to refine the experiments, with excellent agreement between the two. The experimental test-bed facility has been significantly enhanced over the REF period, allowing the generation, transmission and processing of a range of advance modulation formats, in the multiwavelength regime, over 10,000+ km and switching over a range of timescales, down to nanoseconds, for example [IEEE Phot Tech Lett **22** 1714 (2010), ECOC 2012]. It has also been strengthened by the addition of an FPGA-based digital transmitter, developed in collaboration with PG, for generation of Nyquist-spaced channels referred to in section (d). Our plan is to extend the goals of (iii), to maximise the capacity of both the optical channel and the overall optical network, and the development of coding and DSP techniques, for a two order of magnitude increase in capacity. The award of the £4.9 million EPSRC Programme Grant 'UNLOC - Unlocking the capacity of optical communications', will help us achieve this ambitious aim.

PG: In our RAE2008 submission we stated that our key future aims were to create (i) a manufacturable photonic integration technology on silicon (collaboration with EMDG**)**, (ii) compact photonically generated THz systems (collaboration with EMDG and SSCG) and (iii) multichannel high order modulation optical communication systems (collaboration with ONG and CISG). To achieve the first aim we created a new clean room and installed a unique molecular beam epitaxy (MBE) system including phosphorous recovery for the growth of Group III-V materials on silicon. This led to the world's first successful telecommunications wavelength quantum dot lasers to be

grown on Ge, SiGe and silicon substrates [see eg Nature Photonics **5** 416 (2011)]. To meet the second we obtained the £6.65 million EPSRC Programme Grant 'COTS - COherent Terahertz Systems - opening up the terahertz spectrum for widespread application' and have already demonstrated the first photonic THz frequency synthesiser [see eg Optics Express, **21**, 22988 (2013)]. For the third we have developed optical injection phase-locked coherent systems having world record sensitivity, which have also been demonstrated for space applications in collaboration with NiCT, Japan [see J. Lightwave Tech. **15** 2696 (2012)].

Our plan now is to build on the direct integration of lasers on Si to create integrated circuits combining CMOS electronics with Group III-V photonics. To this end, we are extending the MBE clean room and installing an interconnected SiGe MBE growth system. In the THz work we intend to demonstrate the first ultra-high capacity (> 10 Gb/s) THz wireless systems based on photonic signal generation and apply our coherent techniques to quantum state manipulation and information processing applications. In our optical communications work we shall continue to work on comb-based transmission systems in collaboration with ONG, including application to new network designs to support the future internet. In this we will be assisted by our selection as preferred tenderer for EPSRC's £2.5 million National Dark Fibre Infrastructure Service providing an experimental network between the Universities of Bristol, Southampton, Cambridge and UCL, with connections to other European assets via Telehouse, London. Our focus on information transmission and processing from the millimetric to the megametric scale will see new emphasis on plasmonic devices, on interconnects and on photonic analogue-to-digital converters. We will create new liquid crystal-based holographic display devices for information output. Finally, we intend to expand our work in energy related technology, building on our demonstration of high-efficiency quantum dot solar cells grown on silicon and related technologies.

SSCG: The work of the group spans RF, microwave and THz research, in which our RAE2008 aims have been achieved and exceeded in many cases. Notable successes include the first demonstration of airborne passive sensor air target detection and personnel, vehicle and through-wall detection using wireless-based sensing. Circuits and Systems activities have been particularly strong in healthcare technologies with support from EPSRC and the EU (CLONS and NEUWalk), highlights including the 'Active Book' implant, which received extensive media attention (see, http://www.bbc.co.uk/news/science-environment-11814554). Over this period our activities have expanded greatly in geophysical-imaging radar, with support from both EPSRC and NERC, to perform avalanche imaging and Antarctic ice shelf imaging (in conjunction with the Swiss SLF institute and BAS), to better understand the influence of ocean circulation on ice shelf melt rate in view of its potential impact on global sea level rise. The Group's research outputs have been extensive and varied, including IEEE Trans, IET and geophysics journals and a Discovery channel programme, 'X-ray Yellowstone'. Our work with NetRAD, measuring and characterising bistatic clutter, supported by Thales, ONR(G) and the Royal Academy of Engineering, and work on non-linear radar scattering has led to papers in the Roy Soc Proc A [**469** 2160 (2013)]. Knowledge transfer activities have included industry collaborations such as Vodafone (the 'Booster Brolly'), and an Enterprise Award for the wireless detection work, receiving widespread media coverage.

Our strategy for the next period includes building on our success in passive through-wall radar imaging, growing the new JDI Centre for Security Technology and extending our NetRAD multistatic radar system to operate over a range of frequency bands. We plan, also, to continue and expand our geophysical imaging radar interests to include volcano lava lake imaging and polar ice melting. We intend to build on our industry collaborations in radar and antenna systems, including collaboration with Huawei on smart antenna systems for mobile communications. New sensing capabilities and the lack of available bandwidth will lead to intense interest in THz systems, where we plan to exploit photonics-based technologies (eg high spatial and temporal resolution THz imaging and THz spectroscopy technologies) able to effectively address this spectrum (Programme Grant COTS, collaboration with PG). We shall work on new generations of radar systems, for example, inspired by dolphins and capable of very sensitive ways of distinguishing between linear and nonlinear scatterers. In addition, we shall advance research on biomedical sensing and information transmission through new biosensor principles (developed in the LCN) and advanced microelectronic circuit design. One of our ambitious aims is the development of early-warning sensor systems that can test and track serious infectious diseases - such as major flu epidemics, MRSA and HIV - using mobile phones and the internet. The recent

award of the £11 million EPSRC "IRC in Early-Warning Sensing Systems for Infectious Diseases", in which we are a partner, will help us achieve this aim.

c. People, including:

I. Staffing strategy and staff development

In support of our research strategy we have increased our academic staff number from 33 to 38 with high quality appointments, of which 3 have been from overseas, in the following areas: broadband access, CP Liu (from UCL); networks and coding, Andreopoulos (formerly UCLA), Pavlou (from Surrey), Watts (from Cambridge); in quantum devices, Elzerman (from ETH Zurich), Morton (from Oxford), Pepper (from Cambridge); in communications systems and information theory, Masouros (from Belfast), Rodrigues (from Porto); in sensors and biomedical electronics, X Liu (formerly UCL). We have also sought to recognise the importance of energy to all these areas by a targeted appointment, Papakonstantinou (from CERN). Over the next 5 years we intend to increase our academic staff number to 43 with the contracted appointment of RAEng Fellowship Holder, Carrington (silicon photonics), and with further appointments in communications, energy, sensing and information processing. Developments to the physical infrastructure to support this growth are described in Section d. UCL operates a strict policy on **equalities and diversity** (see www.ucl.ac.uk/hr/equalities/) and all Unit staff involved with recruitment receive specialist training. We have also implemented schemes for flexible working to assist with family responsibilities. We expect all academic staff to play an active role in teaching and in the administration of the Unit.

We operate a formal appraisal scheme for the **career development** of all staff members, as well as less formal mentoring through the Group structure. We encourage sabbatical leave, particularly where this can be used to develop collaborations with industry and leading research organisations worldwide. The Unit holds an annual review of academic promotions in which academic staff discuss their promotion cases with their Head of Group and submit a bid for promotion, which is then reviewed by the Unit Professors. Cases that are approved go forward to UCL's academic staff promotions round, while for cases that are not approved the Head of Department meets with the member of staff to advise how to strengthen their case. A measure of our success in career development is the high-level of subsequent appointments. For example, Prof. I Boyd to Director of the Nanotechnology Centre for Nanofabrication, University of Melbourne; Prof. C Baker to Dean and Director of the College of Engineering and Computer Science, Australian National University, and Dr. Y Yang to Director, Shanghai Research Center for Wireless Communications and Professor, Chinese Academy of Sciences and Shanghai Technical University.

We have implemented fully the **Concordat to support the Career Development of Researchers**. Following a probationary period, Research Associates are employed on open-ended contracts. We involve them strongly in interactions with our industrial and other research collaborators. Through appraisal and mentoring we determine with them whether a future career in academia or industry is most suitable. In the former case, we enable them to acquire teaching experience and assist them in applying for personal Research Fellowships. In the latter, we assist them in finding suitable opportunities, through our extensive industrial links. We make full use of the salary flexibility available to us under the unified pay spine to ensure recruitment and retention of key staff.

Within the REF assessment period, we have mentored and supported the Unit's staff in winning a number of **prestigious fellowship awards**: Dr. N Curson (EPSRC Fellowship); Dr. P Warburton (EPSRC Leadership Fellowship); Dr. B Thomsen (EPSRC Advanced Fellowship); Dr. O Mitrofanov (Royal Society University Research Fellowship); Prof. H Liu (Royal Society University Research Fellowship); Dr. C Masouros (Royal Academy of Engineering Research Fellowship); Dr P Watts (EPSRC Career Acceleration Fellowship); Dr J Morton (Royal Society University Research Fellowship); Prof. P Bayvel and Dr J Elzerman (Royal Society Wolfson Research Merit Awards), Prof. H Griffiths (Royal Academy of Engineering / Thales Chair). Staff holding research fellowships are given teaching loads of less than 30 hours pa, compared with our average load of 60 hours pa.

The Unit benefits from the involvement of many **visiting scholars** in its work. During the REF assessment period we hosted over 200 such visitors from companies and research institutes including ANU and DSTO Australia, Ministry of Science Technology and Innovation, Brasil, NiCT and NEC Japan, CERN, Switzerland, Ohio State University, USA.

c. II. Research students

The Unit (via the EEE Department) operates MRes, MPhil, EngD and PhD Programmes supporting over 120 research students, the majority of studentships being collaborative with industry or other research organisations. We have been able to provide support to our strategic themes with the award of two EPSRC Centres for Doctoral Training (CDT) during the assessment period: Photonic Systems Development (joint centre with Cambridge, led by UCL) and Security Science, the latter linking with the UCL Department of Security and Crime Science (lead) and the UCL Departments of Chemistry, Architecture, Computer Science and Laws. Other support comes through UCL's DTG allocation; CASE studentships; two EngD programmes, and industrially-funded PhDs.

We have in place a hierarchy of support for research students; in addition to the individual project supervisor, there is a Departmental Graduate Tutor (Kenyon), a Faculty Graduate Tutor, and UCL's Graduate School dedicated to providing support and professional development opportunities to all our research students. We have an administrative office in the Unit to deal with student issues, to interface with the Registrar's Division and the Graduate School and to publicise careers opportunities. We have specialist administrators and outreach managers for the CDTs.

We **recruit widely** to our programmes via a number of mechanisms: direct recruitment of the best of our graduating undergraduate and Masters' student cohorts with a dedicated site for each CDT as well as advertising widely in the media (New Scientist, IET Engineering & Technology, findaphd.com); via careers fairs - both national and international - and via targeted mail campaigns. We run twilight sessions on 'What a PhD is and How to Choose a PhD' to 3rd and 4th year undergraduates, and the top graduating students are targeted specifically and invited to apply for doctoral study. Every member of staff is expected to supervise research students, and in allocation of students from DTG funding and CDT programmes, an effort is made to support early-stage academics by preferentially allocating students to them, where appropriate.

Our current research student:staff ratio is 3.2:1; it is significant that our doctoral student numbers are growing - our doctoral admissions have increased 33% over the REF period despite a background of reducing funding from RCUK sources. Part of this success can be attributed to the two CDTs that we are involved in – the CDT in Photonic Systems Development and the CDT in Security Science. The former is a joint programme with the University of Cambridge in which students take an initial one-year MRes that includes a comprehensive programme of technical, research skills, and professional development courses, along with two research projects (each of which must be taken at a different centre - UCL, University of Cambridge, or industry). After successful completion, students move to the conventional MPhil/PhD programme, but with an emphasis on Photonic Systems and a particularly close interaction with industry - the majority of the research projects are in collaboration with industry.

Research students are **fully integrated** into the research life of the Unit. They are provided with shared offices housing other students from the same Research Group, and Photonic Systems Development CDT students are provided with a dedicated CDT workroom. Individual research groups run regular discussion meetings, and the CDT students have a weekly coffee morning to encourage informal interaction and cohort building. Students are required to present posters at the Unit's annual Barlow & Mildner lectures during each year of their PhD study, offering networking opportunities with senior academic and industrial partners. Prizes for the best poster and best doctoral thesis are awarded at this event. Students interact more widely within the university through the Graduate School, which provides help, support and advice to research students on matters such as funding and scholarships, college regulations, pastoral issues and teaching opportunities. The Graduate School also runs the Online Graduate Student Log, the principal method for students to maintain a record of their training, meetings with supervisors, periodic reports and project objectives. This, in combination with the Unit's research student administrative support, provides an effective and efficient way to **monitor students' progress**.

The Graduate School also runs a comprehensive **skills development programme** for research students, with courses available on a wide range of topics to enhance students' professional development in areas such as Research Organisation and Governance; Communication, Influence and Impact; Personal effectiveness, and Knowledge and Intellectual Abilities. Courses are available from partner institutions in the Bloomsbury Postgraduate Skills Network, including the Institute of Education and LSE. Within the Unit, these courses are supplemented by the range of

Masters-level technical modules that are made available to all doctoral students: some 38 modules in all, on topics from nanotechnology and quantum computation to optical transmission & networks, radar systems, data networks, and the telecommunications business environment. The Unit has also used its allocation of Roberts Skills training funds to enable research students to attend courses at the London Business School, to take independent language courses and to run workshops and conferences specifically aimed at doctoral students (eg a UK-China summer school on 'trends in cross-disciplinary nano, bio and IT research' (Sept 2012); the London Communications Symposium (an annual event for research students)).

Many of our research students are engaged in cross-disciplinary, inter-departmental or inter-institution research programmes - including the two collaborative CDT programmes mentioned above, an EngD programme in Molecular Modelling and Materials Science run by UCL's Department of Chemistry, and joint projects in which students conduct a significant proportion of their research away from UCL at institutions such as CERN, NPL, DSTL and Boeing. This is in addition to CASE studentships that have provided students the opportunity work to with institutions such as the Forensic Science Service, Thales, BAE Systems and Silixa.

Our doctoral students engage widely with the world outside Academia via mechanisms including KTP programmes, public engagement, and outreach activities. In the former case, we have seconded students to collaborating companies via Knowledge Transfer Studentships to carry out highly industrially relevant work. Such secondments have benefitted the Unit by strengthening industry links, the company by enabling them to develop new technologies, and the students, who often are employed by the company at the end of their PhD. Examples of public engagement and outreach include appearances on the Guardian's Science Weekly podcast, radio interviews, contributions to the Cheltenham Science Festival, and outreach visits to both primary and secondary schools. Students have also contributed to the Royal Society summer science exposition, the Big Bang Fair and the Manchester Science Fair, and to STEMNET, an organisation set up to inspire young people in science, technology, engineering and mathematics.

Our research students are in high demand post-graduation, going on to take up careers in industry, in academic research as postdoctoral researchers, and in many cases continuing to permanent academic positions at such institutions as the University of Liverpool; Queen Mary, University of London; University of British Columbia; Aston University; City University and the University of Hokkaido. Many of our students have taken up senior positions in industry at such companies as Alcatel-Lucent, Nokia-Siemens, Deutsche Telekom, and some have taken up Directorships (Fixnetix, Silixa). Several graduates have been awarded prestigious fellowships, including Leverhulme Trust Early Career Awards (Gavioli, 2006) and EPSRC Fellowships (Watts, 2011). The UCL Careers Service offers customised one-to-one advice sessions with researcher employment specialists and the Unit benefits from industry facing and student facing specialist advisers employed by the Faculty.

Many of our doctoral students have won, or been shortlisted for, major prizes including: shortlisted for the EPSRC ICT Pioneers award (Anastasia, 2011; Cirmirakis, 2012); finalists in Corning Outstanding Student Paper (Mendinueta, 2011; Makovejs, 2010); best student paper awards at ECOC (Behrens, 2011; Bouziane, 2012), IEEE Workshop on Signal Processing Systems (Anastasia, 2009), IEEE Microwave Photonics (Balakier, 2012) and IEEE International Frequency Control Symposium (Moreira, 2012); winners of IEEE Photonics Society Postgraduate Fellowship Prize (Lavery, 2012), and Marconi Society Young Scholar (Lavery, 2013).

Future growth will be assisted by the award to the Unit of a new EPSRC CDT in Integrated Photonic and Electronic Systems (joint centre with Cambridge, led by UCL).

d. Income, infrastructure and facilities

Within the REF assessment period the Unit has been awarded a £3.7 million Basic Technology programme on quantum information processing using silicon and four EPSRC Programme Grants: in Coherent THz Systems (COTS) (£6.65 million); Coherent Optical and Microwave Physics for Atomic-Scale Spintronics in Silicon (COMPASS) (£6.1 million), Nano-electronic Based Quantum Physics (£6.6 million) and Unlocking the Bandwidth of Optical Communications (UNLOC) (£4.9 million). The Unit also leads the £7.2 million EPSRC Centre for Doctoral Training in Photonic Systems Development (joint with the University of Cambridge).

For the REF assessment period, the breakdown of **external funding** awarded for research within the Unit is as follows: Research Council funding: £41,567,349; European Commission funding: £8,370,452; Consultancy and Industrial funding: £3,669,976. In addition, the Unit has held a number of prestigious fellowships during the REF period (see Section c for further details). In total, the Unit has been awarded 191 research grants and contracts with a combined value of £53,607,777 during the REF period.

During the REF assessment period, research space has been expanded and improved through the refurbishment of the Roberts Building and construction of the Engineering Front Building investing in excess of £12 million.

In **research infrastructure** the Unit has been enhanced by investments of over £11.8 million during the REF period, including four major projects from the Capital Investment Fund (CIF): Molecular Beam Epitaxy (MBE) facility for advanced photonic devices - £1.1 million plus £1.5 million in new clean room and associated infrastructure works; new Electron Beam Lithography system £958,000; Converged Network & Systems Labs CONNET £780,000 bridging the work of CISG, ONG, PG and SSCG to research systems for the future Internet, and low temperature lab equipment £710,000 supporting quantum information processing research. EPSRC has also awarded a Strategic Equipment Grant of £420,000 towards the purchase of a Dilution Refrigerator for low temperature experimentation. Other significant capital investments have included: new MBE system for oxides (£373,500); new Focused Ion beam Etcher for information processing devices (£1.5 million) and cryogen-free < 1K refrigerators for quantum information processing work (£1 million); 67GHz Agilent Lightwave Component Analyser (£440,000); Real Time Sampling Oscilloscope System from Agilent (£411,000); 2x DAC II (34 GS/s, 6 bit DACs) and 2x Xilinx Virtex-5 FPGAs forming the programmable digital transmitter within the ONG test-bed (£81,000); Solar Cell Characterisation Test Bed (£96,000); Microwave Vector Signal Analyser (£69,000); Toptica FemtoFiber pro IR 1560nm (£66,000); EEE Department server upgrade (£100,000) and a Spectra-Physics Solid State Laser, Millennia 10W pump for fs pulse THz generation (£50,000).

We received an equipment donation of £1.8 million from Aeroflex to establish a unique wireless and mobile test facility with the capability of generating bespoke wideband signals, in addition to all the standard signal formats, from GSM and WiFi to WiMAX and LTE. Together with the CONNET investment this has extended our capabilities to study future Internet and Wireless technologies leading to 5G systems and beyond. The Unit has also received donated equipment from Pi Photonics, Ciena and Cisco worth over £430,000. The Unit will continue to enhance its infrastructure, with the procurement in FY 2013/14 of an additional MBE system for SiGe, which will cost in excess of £1.5 million, including an extension to the MBE clean room.

e. Collaboration and contribution to the discipline or research base

Collaboration

UCL is highly inter-disciplinary and collaborative, with the Unit being a major catalyst for research and entrepreneurship both within UCL and with leading technology companies. We have extensive on-going industrial and academic collaborations, too numerous to detail here (235 in total over the REF period). Highlight examples of such collaborations include:

Industrial Partnerships: The end-users of our research activities include some of the world's leading technology companies and SMEs. We engage with our industrial partners particularly through collaborative research, but also through joint training and education programmes. These collaborative relationships with industry partners facilitate major impacts on a diverse range of applications. Some key applications and industrial collaborators that the Unit is engaged with include: wireless and optical communications (ADVA, ARM, BT, Cienam, HP, Huawei, IBM, NEC, Nokia, Oclaro, Xyratex), networks (Aeroflex, Ericsson, Cisco), antennas, microwaves and radar (EADS, ESA, Thales, QinetiQ, Guidance Microwave), medical and biomedical diagnostics (CERN, Zilico, Zurich Instruments, inomed, Finetech Medical, Mega Electronics), nanoscale devices and liquid-crystal technology (Philips, Toshiba, BAE Systems, Sharp, Raith, Micron, Sematech), photonics technology (Agilent, Zinwave, u2t Photonics), sensors (Selex, Senceive, Silixa), renewable energy and energy efficiency (NSG/Pilkington, Sharp, Total) and others. We work closely with several SMEs, including Zinwave, Senceive, and TeraView, contributing to their competitiveness through our provision of world-class research facilities and intellectual input to

enhance their research and development capabilities. In collaboration with Aeroflex, we founded the UCL-Aeroflex Lab, a state of the art wireless communications laboratory.

Academic Collaborations: For the purposes of clarity we define a collaboration to be one that has led to a peer-reviewed, co-authored paper and/or a funded research project in the REF period. According to this strict and measurable definition we have over 100 collaborations, including collaborations with over 20 of the world's top 100 universities according to the 2012-2013 Times Higher Education World University Rankings (including Harvard University, Princeton University, ETH Zurich, University of Cambridge, Imperial College London).

Support for Engagement with Industry, Users and Policy Makers: Our engagement with research users and policy makers contributes to impact and adds value to the UK more generally as described in REF3. The Unit has a dedicated Business Development and Marketing Officer, Mr. T Bodley-Scott, who helps to optimise interaction between our research base and its users.

Contribution to the discipline

The list below highlights some of the contributions made by the Unit's staff to their research discipline and how such contributions have been recognised by the research community at large.

i) Society Fellowships: Royal Society (Pepper), Royal Academy of Engineering (Bayvel, Griffiths, Pepper, Seeds), IEEE (Bayvel, Griffiths, Seeds), Optical Society of America (Bayvel), IET (Bayvel, Brennan, Demosthenous, Darwazeh, Griffiths, Mitchell, Seeds, Woodbridge), IoP (Bayvel, Jackman, Kenyon, Pepper, Woodbridge), Institute of Acoustics (Griffiths), Higher Education Academy (Savory, Thomsen, Tong).

ii) Society Boards and Committees: President of IEEE Aerospace and Electronic Systems Society (Griffiths), Vice-President for Technical Activities of IEEE Photonics Society (Seeds), Technical Advisory Council of IEEE Photonics Society (Savory), Vice Chair for Technical Activities of IEEE Committee on Network Operation and Management (Pavlou), IEEE Technical Activities Board (Griffiths), Chair, Young Investigator Award, IEEE Photonics Society (Bayvel), Chair of the Executive of the IET Radar Sonar and Navigation Technical Network (Woodbridge), IEEE CAS Society Analog Signal Processing and Biomedical Circuits and Systems Technical Committees (Demosthenous), Chair of IoP Thin Films and Surfaces Group (Curson), IoP Membership Committee (Jackman), IoP Semiconductor Group Committee (Jackman), IoP Superconductivity Group (Romans), Chair of Campaign for Science and Engineering (Griffiths), Board of Delegates of European Materials Research Society (Kenyon).

iii) Funding agency panels (selected list): EPSRC Prioritisation Panels (Seeds, Thomsen, Warburton, Day), ERC Advanced Grants (Bayvel), Royal Academy of Engineering, Research and Secondments Scheme (Bayvel), Royal Society Industrial Fellowships Committee, Dorothy Hodgkin Fellowships Committee (Bayvel), NSF (Panoiu), French National Research Agency (Jackman, Seeds), Leverhulme Trust Advisory Panel (Seeds), Finnish Academy of Sciences (Seeds), Rank Prize Funds Optoelectronics Committee (Bayvel), EU FP7 Evaluation Panels (Bayvel, Griffin, Kenyon, Papakonstantinou, Pavlou), Royal Society Research Grants (Morton), Portuguese Foundation of Science and Technology Infrastructure Funding Panel (Darwazeh).

iv) Funding agency peer review: All reported staff contribute regularly to peer-review of funding applications submitted to UK research funding agencies (e.g. EPSRC, NERC, TSB, MoD) and many other funding bodies throughout Europe and beyond (e.g. ERC, SNSF Switzerland, ANR France, FCT Portugal, FWO Belgium, NWO Netherlands, NSF USA, Australian Research Council, A*STAR Singapore, CFI Canada, NRC and NSERC Canada, NRF South Africa, ASTF United Arab Emirates).

v) Journal Editorial Board: IEEE Trans Multimedia (Andreopoulos), IEEE Signal Processing Letters (Andreopoulos, Wong), Image and Vision Computing J. (Andreopoulos), IEEE Trans Microwave Theory and Techniques (Darwazeh and Fernandez), IEEE Trans Circuits and Systems I (Demosthenous), IEEE Trans Circuits and Systems II (Demosthenous, Deputy Editor-in-Chief), IEEE Trans Biomedical Circuits (Demosthenous), Physiological Measurements (Demosthenous), IEEE J. Lightwave Technology (Fernandez, Savory), IEEE J. Communications and Networks (Wong), IEEE/OSA J. Optical Communications and Networking (Killey), OSA Optics Express (Panoiu, Savory), IEEE Trans Network and Service Management (Pavlou), IEEE Photonics Technology Letters (Savory, Editor-in-Chief), IEEE Trans Applied Superconductivity (Warburton), IEEE Communications Letters (Wong), IEEE Wireless Communications Letters (Wong), IEEE

Communications – Network and Service Management Series (Pavlou), IET Radar, Sonar and Navigation (Griffiths, Editor-in-Chief), IET Radar, Sonar and Navigation (Woodbridge), IET Optoelectronics (Mitchell, Savory), Int. J. Electrical Eng. Education (Mitchell), Philosophical Trans Royal Society (Pepper), Physical Review (Pepper), Peer-to-Peer Networking and Applications J. (Rio), IET Communication (Wong), Advances in Optoelectronics (Kenyon), Scientific Reports (Morton), IoP Publishing Science Advisory Board (Pepper), China Communications (Darwazeh).

vi) PhD Examiners: All Unit staff frequently examine PhD students (on average 3 per year per staff member) at universities throughout the UK and worldwide (eg Hong Kong PolyU, Nanyang technological University (NTU), Chalmers University (Sweden), KTH (Sweden), TU Delft).

vii) Keynote and invited speakers: Staff accept many invitations to give keynote and invited talks at leading international meetings in their research fields. Highlights include the following keynote talks: ACP 2012 (Bayvel), ICTON 2012 (Bayvel), ECOC 2009 (Bayvel), Nano S&T 2011 (Curson), SPS 2012 (Curson), IEEE CSNDSP 2008 Keynote and 2012 Plenary-opening address (Darwazeh), MRS Spring Meeting 2012 (Jackman), NANOSMAT 2010 & 2012 (Jackman), ICTON 2013 (Killey), IPC 2011 (Killey), OFC 2011 (Killey), RADAR 2011 & 2013 (Griffiths), ECOC 2009 (Mitchell), ECOC 2012 (Mitchell), ICMAT 2011 (Mitrofanov), IRMMW-THz 2011 (Mitrofanov), APS Meeting 2009 & 2011, (Morton), ICDS 2013, (Morton), MNE 2013 (Morton), IEEE/IFIP Manweek 2009 (Pavlou), IEEE/IFIP IM 2011 (Pavlou), IEEE WoWMoM 2011 (Pavlou), IEEE ISCC 2011 (Pavlou), IEEE IIHMSP 2012 (Pavlou), IEEE ITC 2012 (Pavlou), IFIP/IEEE CNSM 2013 (Pavlou), TIDS 2012 (Pepper), ASC 2012 (Romans), ICC3 Osaka (Romans), ISEC 2009 (Romans), ECOC 2008 (Savory), OFC/NFOEC 2008 (Savory), OFC/NFOEC 2012 (Savory), OECC/PS 2013 (Savory), ACOFT 2010 Keynote (Savory), ACP 2011 (Savory), ICSM,(Warburton), Mesoscopic Superconductivity 2011(Warburton), THz Superconducting Electronics 2011 (Warburton).

viii) Awards: 2013 IET Faraday Medal (Pepper), Royal Society Wolfson Research Merit Award (Bayvel, Elzerman), 2014 Clifford Paterson Prize Lecture, Royal Society (Bayvel), IEEE Photonics Society 2013 Engineering Achievement Award (Bayvel), NATO SET Panel Excellence Award (Griffiths), IET A F Harvey Prize (Griffiths), 2013 IoP Moseley Medal and Prize (Morton), Member Academia Europae (Pepper, 2012), 2012 IoP Gold Medal for Business and Innovation (Pepper), IoP Honorary Fellowship (Pepper, 2012), UCL Award for Enterprise 2013 (Bayvel), 2012 IoP BRSG-NMRDG Annual Prize for Excellent Contribution to Magnetic Resonance (Morton), IEEE Integrated Management Dan Stokesbury Award (Pavlou), IEEE Communications and Information Theory Societies Joint Paper Award 2011 (Rodrigues), 2012 IoP Gabor Medal and Prize (Seeds).

ix) Conference chair/organising committee: IEEE DSP 2013 (Andreopoulos), MMM 2012 (Andreopoulos, Co-Chair), 2008 IEEE Broadnets (Darwazeh, General Chair), 2008 IEE Conf on Wireless Networks (Darwazeh, Co-Chair), IEEE VLSI-SoC 2011,12,13 (Demosthenous), ESSCIRC 2008,09,10,11,12,13 (Demosthenous), BioCAS 2013 (Demosthenous), Radar 2013 (Griffiths, Woodbridge), I-MRC 2011 (Jackman), IUMRS-ICEM 2012 (Jackman), E-MRS Fall 2011 (Kenyon), ECOC 2013 (Killey; Savory, Subcommittee Chair; Bayvel, Local Organising Chair), OECC 2008,09 (Killey), CLEO 2008 (Mitrofanov), The Royal Society URF Conf 2011 (Mitrofanov), Rocky Mountain Conf for Magnetic Resonance 2012,13 (Morton), OSA Renewable Energy and the Environment Conf 2011,12,13 (Papakonstantinou), IFIP/IEEE MMNS 2008 (Pavlou), OFC/NFOEC 2013 (Savory, Program Chair; Seeds, Sub-Committee Chair), OSA SPPCom 2010 (Killey, General Chair), OSA SPPCom 2011,12 (Savory, Program Chair), IEEE Photonics Society Summer Topical Meeting 2013 (Thomsen, Program Chair), AOC 2012 (Warburton, Chair).

x) Other significant contributions:

Invited expert witness (England High Court of Justice) on two major patent litigation cases (IPCOM vs Nokia, 2009) and (Samsung vs Apple 2012) (Darwazeh); UK representative of NATO Panels SET 186 and SET 196 (Woodbridge); Co-Chair of NATO SET-182 Task Group (Griffiths); MoD DSAC member (Griffiths), DSAC Register of Experts (Bayvel); IEEE AES Distinguished Lecturer (Griffiths); Member of the Rolls-Royce Electrical, Control & Electronics Advisory Board (Brennan).

Consultant/advisor: Acacia Communications (Savory), BioNanoConsulting (Demosthenous), Boult Wade Tennant LLP (Brennan), BskyB (Mitchell), Creomedical (Darwazeh), Freshfields LLP (Darwazeh), DSTL (Tong), Global Invacom (Tong), Guidance Microwave (Brennan), Hogan Lovells LLP (Tong), Huawei (Bayvel, Killey, Savory), L-3 TRL (Tong), Mundio Mobile (Darwazeh and Rio), PMC-Sierra Ltd (Savory), Powell Gilbert LLP (Brennan), Taseon (Savory, Thomsen), Taylor Wessing LLP (Brennan), Thales (Seeds), u2t Photonics (Seeds), Vodafone (Tong).