Description of Ph.D. project in EXSS for Oct 2023 Entry

Project title:	**Neuromorphic Computing for Low-Energy AI**

Principal Supervisor:	Dr Jack C. Gartside	Project No:	JCG_01
Email:	j.carter-gartside13@imperial.ac.uk		
Other supervisors:	Will R. Branford- w.branford@imperial.ac.uk Riccardo Sapienza- r.sapienza@imperial.ac.uk		

Aims of the project: Artificial Intelligence (AI) has an energy problem. While it offers to revolutionise many aspects of industry and society - it does so at a cost. The global carbon-footprint of AI is shocking, training a large neural net currently generates up to **280 tons CO2**, and the energy consumed globally by machine learning is **doubling every 3.5 months**. These exponentially spiralling costs are unsustainable and unacceptable, presenting a real threat to a zero-carbon future.

Neuromorphic computing may offer us a solution. By leveraging the nonlinear dynamics of complex physical systems to perform machine learning, neuromorphic computing promises **radically lower energy-consumption** than conventional computers.

The original maths behind software neural networks were invented by physicists to describe strongly-interacting magnetic networks ('Hopfield' networks or 'Spin Glasses').

Inspired by similarities between these networks and neurons in our brain, machine learning researchers used these mathematical frameworks for AI and the rest is history, with the current successes of Google Deepmind etc originating in part from these magnetic network roots.

Since the early successes of software neural networks, researchers have dreamt of implementing machine learning directly in magnetic arrays, bypassing the software layer of abstraction and increasing energy efficiency. Until recently, the engineering challenges of inputting and reading-out data from complex magnetic networks meant these ideas remained unrealised.

Recently, our team at Imperial College solved these engineering problems to **implement machine learning** directly in **nanomagnetic networks**, a world-first.

We have ambitious ideas to take nanomagnetic neural networks far beyond our initial proof-of-concept published recently in Nature Nanotechnology. We have just published a second scheme interconnecting multiple magnetic arrays, acting as separate layers in a larger neural network. We will combine our expertise in magnonics/spin-wave engineering with All-Optical Magnetic Writing requiring zero magnetic field, to develop next-generation low-power hardware & help solve the pressing AI energy crisis. We have two patents on our technology, and all team members will have the opportunity to participate in the commercial/industrial and IP side of our projects in addition to academic research.

By joining us on our journey, you will gain cutting-edge machine learning & nanotechnology skills. This PhD will place you at the forefront of the fast-moving new field of physical neuromorphic computing & give your research the chance to help solve a pressing global environmental issue.

We are looking for: Creative & motivated researchers, excited by the opportunity to be involved with both laboratory nanotechnology & machine learning coding. Experimental techniques (experience a bonus but not necessary) include electron beam lithography, ferromagnetic resonance and magnetic force microscopy. Software is currently primarily Python machine learning libraries: sklearn, pyTorch, Tensor Flow.

Techniques, activities, and equipment used:

Machine learning coding: Python, sklearn, pyTorch, Tensor Flow

Nanofabrication: Electron beam lithography, magnetron sputtering, thermal evaporation.

Characterisation: Magnetic force microscopy, Magneto-optical Kerr Effect, Kerr microscopy, VSM, Ferromagnetic resonance, Brillouin light-scattering, Photoluminescence / Pump-probe optical measurements

Locations of equipment / collaborators:

Primarily South Kensington campus Imperial College London

Description of Ph.D. project in EXSS for Oct 2023 Entry

Project title:	**Optimising photochemical solar energy conversion in natural and artificial molecular systems**

Principal Supervisor:	Prof Jenny Nelson	Project No:	JN_01
Email:	Jenny.nelson@imperial.ac.uk47851		

The underlying processes that convert solar photons into chemical or electrical energy in organic solar cells and in natural photosynthetic systems have many features in common [1,2]. In both cases, solar photons are absorbed by an assembly of molecules, followed by diffusion of the photogenerated exciton, dissociation into separated charges and separation of the charges across the device or membrane. Natural photosystems achieve charge separation with high quantum efficiency and with low apparent energy losses, suggesting that aspects of the structure of photosystems could be beneficial for artificial systems like solar cells. Thanks to their well understood structure they provide appealing model systems in which to study the process of photoinduced charge separation. For both photosystems and solar cells, the light emitted by the system when illuminated or subject to applied bias (i.e. luminescence), carries information about the different processes involved in the photochemical process and is key to understanding behaviour [3].

The aim of this project is to develop a physics-based model of photochemical solar energy conversion that can be applied in parallel to photosystems and molecular solar cell structures, and use it along with experimental data to better understand the function of photosystems and optimise the design of solar cells.

The project has the following objectives:

1) To develop an existing model of the quantum dynamics of excitations in molecular systems to simulate the process of solar photochemical energy conversion in either photosystems or molecular solar cells.
2) To use experimental measurements of light absorption and emission in such systems along with the model to identify the factors limiting energy conversion efficiency and suggest improved designs.
3) To apply the methods to recently discovered varieties of photosystem in order to understand how they manage to drive photochemical reactions with light of lower energy than standard photosytems without loss in quantum efficiency [4].
4) To use the understanding gained to suggest new arrangements of molecules in organic solar cells that could lead to improvements in the conversion efficiency by reducing non-radiative energy losses [3].

References

[1] R. T. Ross "Some Thermodynamics of Photochemical Systems" J Chem Phys 46, 4590 (1967);

[2] J. L. Bredas et al "Photovoltaic concepts inspired by coherence effects in photosynthetic systems" Nature Reviews Materials (2016) http://dx.doi.org/10.1038/nmat4767

[3] M. Azzouzi et al, "Factors Controlling open-circuit voltage losses in organic solar cells" Trends in Chemistry (2019) https://spiral.imperial.ac.uk/handle/10044/1/84751

[4] S. Viola et al. (2022). "Impact of energy limitations on function andresilience in long-wavelength photosystem II" eLife (2022) https://doi.org/10.7554/elife.79890

Techniques, activities, and equipment used:

The project contains both computational and experimental elements. The extent of experimental part can be varied depending on the interests and skills of the student.

Computational: Modelling using kinetic (rate equation) models; quantum chemical modelling of excited states, their properties and their dynamics; simulation of structures, possibly using molecular dynamics or QM/MM; option to use non-adiabatic excited-state molecular dynamics methods. The exploration of new solar cell structures could involve high throughput computational screening methods.

Experimental: The experimental part would involve measurement of delayed and prompt luminescence of either organic solar cells or different types of photosystem (using samples prepared by collaborators), under different temperature and environment (changing the light colour or intensity, local electrochemical gradient, electric field or the solvent).

Locations of equipment / collaborators:

Prof Bill Rutherford (Dept of Life Sciences, Imperial College)

Description of Ph.D. project in EXSS for Oct 2023 Entry

Project title:	Device physics of single-component organic solar cells

Principal Supervisor:	Prof Jenny Nelson	Project No:	JN_02
Email:	Jenny.nelson@imperial.ac.uk		

Organic semiconductors are attractive materials for solar photovoltaic energy conversion because of the tuneability of their properties, ease of processing and short energy payback times. Improvements in the design of molecular materials has almost doubled the power-conversion efficiency of organic photovoltaics in the last 5 years, from 11 to 19%.[1][1] Traditionally, an organic solar cell comprises two materials, a donor and an acceptor, which are considered essential for achieving good charge-generation efficiency. Recently, several alternative routes to photogeneration in organic materials have emerged. In one, so called single component materials have been developed in which photogeneration is achieved in films of macromolecules that contain electron-donating and electron-accepting parts chemically bound together [2]. Such an approach offers better control over interface structure and device stability than the conventional blend approach. In another development, studies have reported that some high-performing acceptors can achieve relatively high charge-generation efficiency in the absence of a donor [3]. This challenges the current understanding of how photogenerated excitons dissociate into free charges in organic semiconductors [4]. It raises the question of whether a donor-acceptor interface is necessary for high-efficiency solar cells. The goal of this project is to establish the conditions in which a single-component device would suffice, and to develop molecular design criteria to maximise charge pair generation from the light absorbing component.

This project will focus on fabrication and measurement of single-component devices using chemically bound donor-acceptor structures or series of molecular acceptors with the aim of understanding what chemical or microstructural properties are necessary for photo-charge generation. Both experimental (field- and temperature- dependent charge-generation measurements, temperature dependent spectroscopy (e.g. luminescence),) and/or modelling (electron-transfer rate modelling, electronic structure calculations and device physics models) approaches will be applied.

The combination of experimental and modelling techniques will allow to identify the parameters controlling the electron transfer processes for each material system; and to study the relationship between the calculated rate constants and the measured dynamics of charge transfer. These results will help to identify which chemical-structural features control the exciton dissociation and charge separation processes. For example, structural heterogeneity, reorganisation energy and vibrational modes involved in charge transfer will be of interest. The information obtained can be used to design materials with that could lead to higher single-component device performance. There will be options for new material designs to be synthesised and tested.

References

[1] A. Armin, et al., Advanced Energy Materials, 11 (2021) 2003570. doi: https://doi.org/10.1002/aenm.202003570

[2] M.B. Price, et al., Nature Communications, 13 (2022) 2827. doi: https://doi.org/10.1038/s41467-022-30127-8

[3] J. Min et al., Joule 5, 1800 (2021) https://doi.org/10.1016/j.joule.2021.05.002

[4] O.P. Dimitriev, Chemical Reviews, 122 (2022) 8487-8593. doi: https://doi.org/10.1021/acs.chemrev.1c00648

Techniques, activities, and equipment used:

The project contains both computational and experimental elements. The extent of computational part can be varied depending on the interests and skills of the student.

Computational: Modelling using kinetic (rate equation) and semiconductor device physics models; quantum chemical modelling of organic semiconductors; possibility to use high throughput computational screening methods.

Experimental: The project will allow the student to develop experimental skills in device fabrication, opto-electronic characterisation characterisation, data analysis and modelling of soft electronic materials.

Locations of equipment / collaborators:

Dr Artem Bakulin (Dept of Chemistry, Imperial College)

Dr Flurin Eisner, Dr Mohammed Azzouzi (EXSS)

Description of Ph.D. project in EXSS for Oct 2023 Entry

Project title:	**Organic Photodetectors for high Performance Image Sensors**		
Principal Supervisor:	Prof Ji-Seon Kim	Project No:	JSK_01
Email:	ji-seon.kim@imperial.ac.uk		

Aims of the project:

Organic semiconductors such as small molecules and conjugated polymers are a new class of attractive photoactive materials for photo-sensing in various imaging applications. Their narrow optical absorption bands, combined with highly flexible, light weight, transparent and easily processable physical properties are particularly advantageous for top-surface photodetection in integrated sensor arrays to achieve compact and sensitive high-resolution imaging systems. For organic photodetectors (OPD), this photoactive layer is typically comprised of a bulk heterojunction (BHJ), a highly intermixed blend of electron donor and electron acceptor molecules, which offer efficient separation of excited state excitons into charge carriers at their donor/acceptor interfaces. In particular, the OPDs based on conjugated polymer donor and non-fullerene acceptor (NFA) BHJs have demonstrated great potential for high-performance light-sensing applications, thanks to wide materials optoelectronic tunability by molecular design. However, state-of-the-art OPD devices still lack behind silicon-based counterparts in terms of low dark current, detectivity and fast photodetection. In this project, we will investigate the role of BHJ on OPD device parameters (a) by controlling the donor/acceptor blending ratio, (b) by changing the molecular structures of polymer donor and NFAs, and (c) by using single-component material systems. Based on this work, we aim not only to fabricate efficient OPD devices, but also to understand the fundamental operational mechanism of OPD devices which is different from organic photovoltaic (OPV) devices.

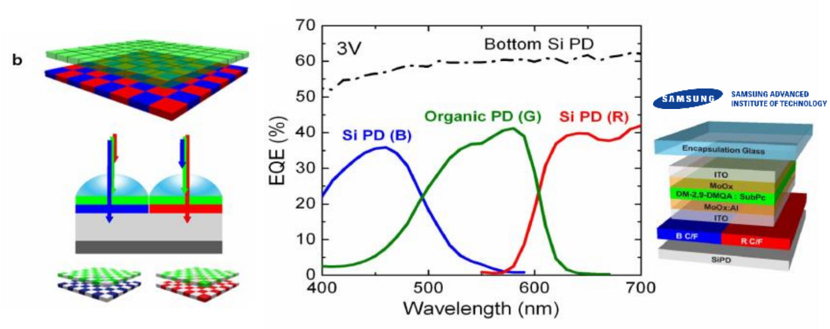


Image R, G, B sensor array where OPD is used as a green-light sensor. By using OPD as the green sensor, no pixelated green colour filter is needed saving fabrication steps and cost.

See more details in https://www.imperial.ac.uk/nanoanalysis-group/

References:

Labanti, C., Wu, J., Shin, J., Limbu, S., Yun, S., Fang, F., . . . Kim, J. -S. (2022). Light-intensity-dependent photoresponse time of organic photodetectors and its molecular origin. *NATURE COMMUNICATIONS*, *13*(1), 10 pages. doi:10.1038/s41467-022-31367-4

Limbu, S., Park, K. -B., Wu, J., Cha, H., Yun, S., Lim, S. -J., . . . Kim, J. -S. (2021). Identifying the Molecular Origins of High-Performance in Organic Photodetectors Based on Highly Intermixed Bulk Heterojunction Blends. *ACS NANO*, *15*(1), 1217-1228. doi:10.1021/acsnano.0c08287

Lee, T. H., Dong, Y., Pacalaj, R. A., Park, S. Y., Xu, W., Kim, J. -S., & Durrant, J. R. (2022). Organic Planar Heterojunction Solar Cells and Photodetectors Tailored to the Exciton Diffusion Length Scale of a Non-Fullerene Acceptor. *ADVANCED FUNCTIONAL MATERIALS*, 9 pages. doi:10.1002/adfm.202208001

Techniques, activities, and equipment used:

OPD device fabrication and characterisation techniques (such as JV and EQE), as well as advanced spectroscopy techniques including confocal Raman spectroscopy, surface photovoltage spectroscopy (SPV), ambient photoemission spectroscopy (APS) will be used. This project will also involve theoretical simulations of molecules in terms of energy levels and molecular structures utilizing density functional theory.

Skills to be learned:

- Literature Survey (including device physics, molecular physics, and materials science)
- Scientific Research: Experimental (optoelectronic characterizations, photoemission spectroscopy, surface photovoltage spectroscopy, Raman spectroscopy); Theoretical (Density Functional Theory); Data processing (scripting), analysis, and interpretation.
- Professional skills: teamwork, project management, time management, and scientific presentation.

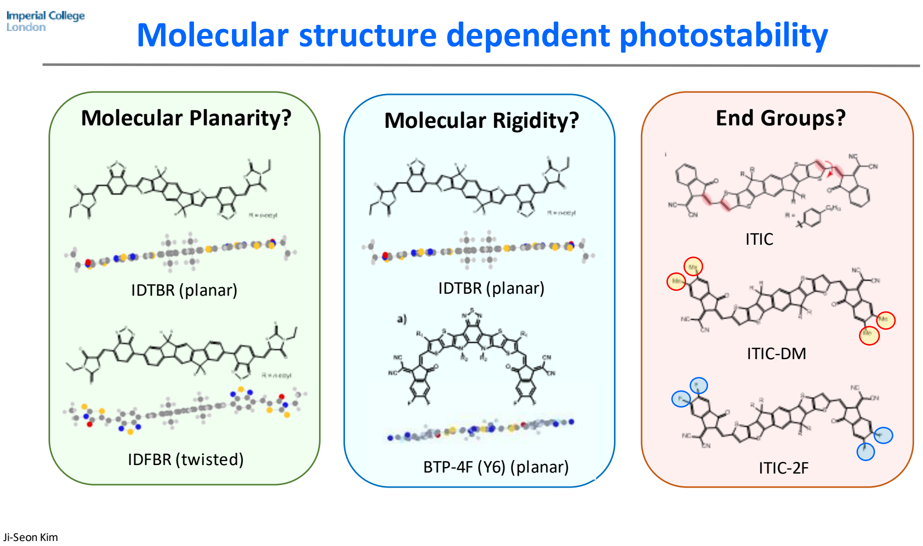
Locations of equipment / collaborators:

Most equipment for device fabrication and characterisation is based at IC. The project will include collaborations with other academic (e.g. Imperial, Korea U, GNU) and industrial (e.g. Samsung) partners in OPD research. The project will be aligned with our recently awarded Samsung research project to develop high performance OPDs using NFAs.

Description of Ph.D. project in EXSS for Oct 2023 Entry

Project title:	**Stability of Organic Solar Cells Towards Commercialisation**		
Principal Supervisor:	Prof Ji-Seon Kim	Project No:	JSK_02
Email:	ji-seon.kim@imperial.ac.uk		
Other supervisors:	Dr Julie Euvrard email : julie.euvrard@imperial.ac.uk		

Aims of the project: Organic solar cells (OSCs) have attracted enormous interest in scientific research and commercial development due to their low-cost, flexible, solution processable properties. Solution-processed OSC devices are typically based on an organic bulk heterojunction blend consisting of a conjugated donor polymer and a small molecule acceptor. With newly developed non-fullerene acceptors (NFAs), their efficiencies have reached impressive level of >18%. However, the poor operational lifetimes of many high performing devices limit their use in commercial modules. It is therefore important to understand the degradation mechanisms of these materials to enable the synthesis of more stable materials. In this project, we will investigate the photostability of the state-of-the-art donor polymers and NFAs including well-known PM6 and Y6 and their derivatives, as well as new photovoltaic materials. The exact molecular origins of the photostability will be identified through in-depth investigations using an assay of in situ spectroscopy techniques such as molecular vibrational Raman spectroscopy combined with molecular simulations. Based on the stability and the rate of photodegradation product formation, we will correlate the molecular structure to its photostability, and the impact that has on overall donor/acceptor bulk-heterojunction blend morphological stability. By doing so, we aim to demonstrate highly efficient and stable organic solar cells and to provide a new synthetic direction for photostable organic photovoltaic materials.



References:

Labanti, C., Wu, J., Shin, J., Limbu, S., Yun, S., Fang, F., . . . Kim, J. -S. (2022). Light-intensity-dependent photoresponse time of organic photodetectors and its molecular origin. *NATURE COMMUNICATIONS*, *13*(1), 10 pages. doi:10.1038/s41467-022-31367-4

Luke, J., Yang, E. J., Chin, Y. -C., Che, Y., Winkler, L., Whatling, D., . . . Kim, J. -S. (2022). Strong Intermolecular Interactions Induced by High Quadrupole Moments Enable Excellent Photostability of Non-Fullerene Acceptors for Organic Photovoltaics. *ADVANCED ENERGY MATERIALS*, *12*(30), 11 pages. doi:10.1002/aenm.202201267

Lee, H. K. H., Stewart, K., Hughes, D., Barbe, J., Pockett, A., Kilbride, R. C., . . . Tsoi, W. C. (2022). Proton Radiation Hardness of Organic Photovoltaics: An In-Depth Study. *SOLAR RRL*, *6*(6), 10 pages. doi:10.1002/solr.202101037

Park, S. Y., Labanti, C., Luke, J., Chin, Y. -C., & Kim, J. -S. (2021). Organic Bilayer Photovoltaics for Efficient Indoor Light Harvesting. *ADVANCED ENERGY MATERIALS*, *12*(3), 10 pages. doi:10.1002/aenm.202103237

Labanti, C., Sung, M. J., Luke, J., Kwon, S., Kumar, R., Hong, J., . . . Kim, J. -S. (2021). Selenium-Substituted Non-Fullerene Acceptors: A Route to Superior Operational Stability for Organic Bulk Heterojunction Solar Cells. *ACS NANO*, *15*(4), 7700-7712. doi:10.1021/acsnano.1c01345

Wu, J., Lee, J., Chin, Y. -C., Yao, H., Cha, H., Luke, J., . . . Durrant, J. R. (2020). Exceptionally low charge trapping enables highly efficient organic bulk heterojunction solar cells. *ENERGY & ENVIRONMENTAL SCIENCE*, *13*(8), 2422-2430. doi:10.1039/d0ee01338b

Luke, J., Speller, E. M., Wadsworth, A., Wyatt, M. F., Dimitrov, S., Lee, H. K. H., . . . Kim, J. -S. (2019). Twist and Degrade-Impact of Molecular Structure on the Photostability of Nonfullerene Acceptors and Their Photovoltaic Blends. *ADVANCED ENERGY MATERIALS*, *9*(15), 14 pages. doi:10.1002/aenm.201803755

See more information about techniques in https://www.imperial.ac.uk/nanoanalysis-group.

Techniques, activities, and equipment used:

OPV device fabrication and characterisation techniques (such as JV and EQE), as well as advanced spectroscopy techniques including confocal Raman spectroscopy, surface photovoltage spectroscopy (SPV), ambient photoemission spectroscopy (APS) will be used. This project will also involve theoretical simulations of molecules in terms of energy levels and molecular structures utilizing density functional theory.

Skills to be learned:

- Literature Survey (including device physics, molecular physics, and materials science)
- Scientific Research: Experimental (optoelectronic characterizations, photoemission spectroscopy, surface photovoltage spectroscopy, Raman spectroscopy); Theoretical (Density Functional Theory); Data processing (scripting), analysis, and interpretation.
- Professional skills: teamwork, project management, time management, and scientific presentation.

Locations of equipment / collaborators: Most equipment for device fabrication and characterisation is based at IC. The project will include collaborations with other academic (e.g. Imperial, GNU) and industrial (e.g. Oninn) partners in OPV research. The project will be aligned with our awarded EPSRC ATIP project to develop large area integrated organic solar cells for targeted applications.

Description of Ph.D. project in EXSS for Oct 2023 Entry

Project title:	**Organic Biosensors for Non-invasive Diagnostics**

Principal Supervisor:	Prof Ji-Seon Kim	Project No:	JSK_03
Email:	ji-seon.kim@imperial.ac.uk	Telephone	ext.47597

Aims of the project: Printable organic biosensors fabricated from solution-processed π-conjugated polymers (π-CPs) are promising candidates for noninvasive diagnoses via the monitoring of biomarkers (i.e. volatile organic compounds) in exhaled human breath. These sensors require good sensing capabilities to transduce stimuli from specific volatile organic compounds at concentrations below 1 ppm (parts per million) into analytical electric signals. However, current organic biosensors do not satisfy the essential requirements for practical medical applications due to the low sensing capability of π-CPs. In this project, we aim to develop a new stimulus-to-signal transducer sensor system comprising ionic liquid electrolytes and pi-conjugated polymers, to form an interpenetrating network at a molecular level critical for a fast stimulus-to-signal transducing with high sensitivity, responsibility and reliability. We will focus on materials design/synthesis, materials/device characterisation, and sensor platform technology development. The success of this project will offer a new class of materials for printed biosensor applications, as well as will provide significant intellectual merit by unveiling fundamental device operational mechanism.

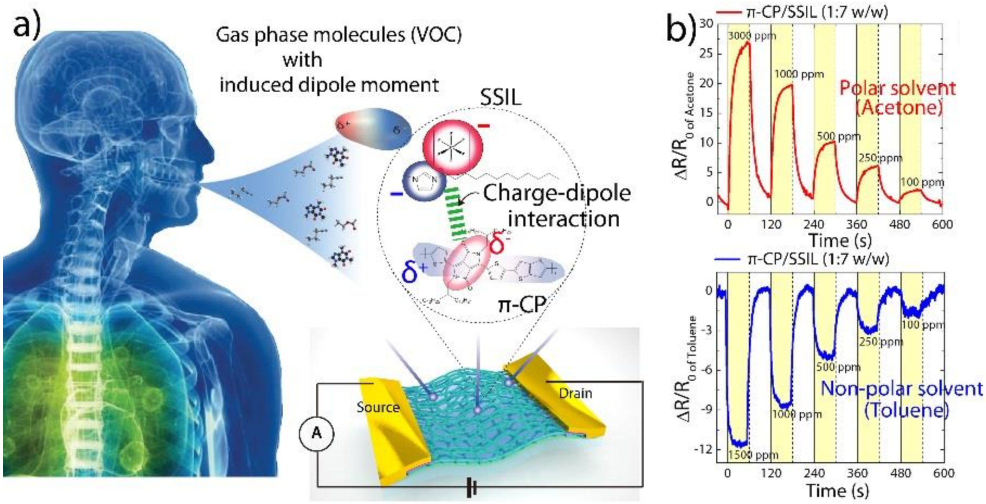


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Figure 1. (a) Schematic images of the novel π-CP/SSIL complex molecular sensor and (b) Initial experimental results of polar and non-polar VOC detection as a resis tance change of the device.

Stewart, K., Limbu, S., Nightingale, J., Pagano, K., Park, B., Hong, S., . . . Kim, J. -S. (2020). Molecular understanding of a pi-conjugated polymer/solid-state ionic liquid complex as a highly sensitive and selective gas sensor. *JOURNAL OF MATERIALS CHEMISTRY C*, *8*(43), 15268-15276. doi:10.1039/d0tc03093g

Kwon, S., Pak, Y., Kim, B., Park, B., Kim, J., Kim, G., . . . Lee, K. (2020). Molecular-level electrochemical doping for fine discrimination of volatile organic compounds in organic chemiresistors. *JOURNAL OF MATERIALS CHEMISTRY A*, *8*(33), 16884-16891. doi:10.1039/d0ta05530a

Limbu, S., Stewart, K., Nightingale, J., Yan, H., Balamurugan, C., Hong, S., . . . Kim, J. -S. (2021). Solid-State Ionic Liquid: Key to Efficient Detection and Discrimination in Organic Semiconductor Gas Sensors. *ACS APPLIED ELECTRONIC MATERIALS*, *3*(5), 2152-2163. doi:10.1021/acsaelm.1c00157

See more information about techniques in https://www.imperial.ac.uk/nanoanalysis-group.

Techniques, activities, and equipment used:

Organic sensor device fabrication and characterisation techniques, as well as advanced spectroscopy techniques including E-field dependent Raman spectroscopy, Ambient Photoemission Spectroscopy (APS), and Atomic Force Microscopy (AFM) will be used. This project will also involve theoretical simulations of molecules in terms of vibrational modes of molecules using density functional theory.

Skills to be learned:

- Literature Survey (including device physics, molecular physics, and materials science)
- Scientific Research: Experimental (optoelectronic characterizations, photoemission spectroscopy, Raman spectroscopy); Theoretical (Density Functional Theory); Data processing (scripting), analysis, and interpretation.
- Professional skills: teamwork, project management, time management, and scientific presentation.

Locations of equipment / collaborators:

Most equipment for device fabrication and characterisation is based at IC. The project will include collaborations with other academic (e.g. Imperial, Dong Guk Univ, GNU) partners in organic sensor research.

Description of Ph.D. project in EXSS for Oct 2023 Entry

Project title:	**Understanding the role of organic ligands on charge transport and photocurrent generation in layered perovskites**		
Principal Supervisor:	Dr Julie Euvrard	Project No:	JE_01
Email:	julie.euvrard@imperial.ac.uk		
Other supervisors:	Prof Ji-Seon Kim- ji-seon.kim@imperial.ac.uk		

Aims of the project: Halide perovskites show great potential for solar energy applications as perovskite solar cells now achieve efficiencies as high as 25.7% for single junction devices.[1] Unfortunately, the rise of perovskite solar cells is hindered by their strong sensitivity to moisture, oxygen, illumination, thermal and bias stresses.[2] Progress in encapsulation technologies alone will not suffice to allow market entry of perovskite solar cells.
It is therefore crucial to tackle the question of stability.

In order to protect halide perovskite films from moisture, a key trigger of degradation in perovskite-based devices, larger and hydrophobic organic cations (ligands) have been introduced in the crystal lattice.[3] As a consequence, the crystal phase is modified to form a 2D- or *layered* perovskite structure with slabs of inorganic octahedra separated by ligands (Fig. 1). While this modification offers higher environmental stability, it comes at the cost of performance with a drastic loss in solar cell efficiency, in part due to a significant disruption of charge transport and exciton dissociation.[4]

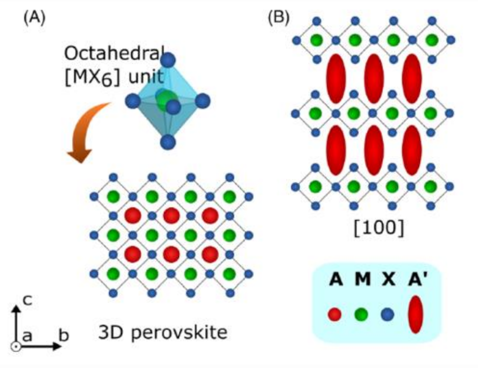

Fig. 1. (A) 3D perovskites lattice and its octahedral unit. (B) 2D perovskite slabs with larger organic cation (ligands). (Fig. from Ref. 4)

In view of this challenge, two research directions are currently being explored: 1) creating a mixed 3D-2D perovskite structure to find a reasonable balance between stability and efficiency;[5] and 2) finding the appropriate ligand to limit its negative impact on efficiency.[6] In this project we will focus on the second aspect *and will aim at improving our understanding of the impact of ligands on charge transport and exciton dissociation in layered perovskites*. In particular, we will tune the length of the organic ligand and follow its impact on various transport and optoelectronic properties of the semiconducting film. We will also explore the influence of the Van der Waals gap between organic ligands present in the Ruddlesden-Popper phase by comparing its properties with the Dion-Jacobson phase (Fig. 2). *The goal of this study will be to determine experimentally a maximum ligand size to ensure sufficient coupling between inorganic slabs.* In addition, *we will ascertain whether the Dion-Jacobson phase should be preferred to the Ruddlesden-Popper one*, which is currently the main focus of research efforts in 2D-3D perovskite solar cells.

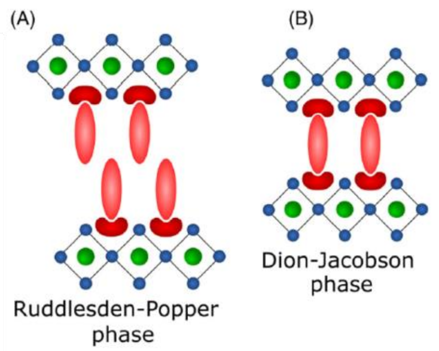

Fig. 2. Organization of ligands (red) in the Ruddlesden-Popper phase (A) and Dion-Jacobson phase (B). The Van de Waals gap is situated between the ligands in the Ruddlesden-Popper phase. (Fig. from Ref. 4)

[1] NREL, *National Renewable Energy Laboratory. Best Research-Cell Efficiency Chart*, **2021**.

[2] L. Schmidt-mende, V. Dyakonov, S. Olthof, L. Schmidt-mende, V. Dyakonov, S. Olthof, F. Ünlü, S. Mathur, D. C. Lupascu, L. M. Herz, A. Chernikov, O. Shargaieva, C. Cocchi, E. Unger, T. Mayer, A. Di Carlo, *APL Mater.* **2021**, *9*, 109202.

[3] T. L. Leung, I. Ahmad, A. A. Syed, A. Man, C. Ng, *Commun. Mater.* **2022**, *3*, 1.

[4] M. S. Holanda, R. F. Moral, P. E. Marchezi, F. C. Marques, A. F. Nogueira, *EcoMat* **2021**, *3*, e12124.

[5] A. Caiazzo, R. A. J. Janssen, *Adv. Energy Mater.* **2022**, 2202830.

[6] H. Fu, *J. Mater. Chem. C* **2021**, *9*, 6378.

Techniques, activities, and equipment used: To tackle this research project, we will combine electrical, optical and material characterization techniques. Material (SEM, XRD, AFM) and optical (UV-visible absorption, photoluminescence) will be carried out to determine and control the morphology and quality of the films explored. Electrical characterizations including variable temperature conductivity and photoconductivity measurements (as a function of light intensity and wavelength) will be used to assess transport and optoelectronic properties and explore the impact of ligands on charge transport and photogeneration of carriers in- and out-of-plane. Additional advanced characterization techniques such as air photoemission spectroscopy (APS) and surface photovoltage (SPV) measurements with be performed in Prof Ji-Seon Kim's lab to deepen our understanding of defects and optoelectronic properties. Samples (thin films and devices) will be fabricated using solution and evaporation deposition techniques in inert atmosphere (glovebox).An important asset to this project will be the use of *advanced Hall effect measurements (including photo-Hall and variable temperature Hall effect) in collaboration with IBM*. Optimized samples will be sent to IBM and measurements will be conducted remotely. Full analysis of the data will be performed at ICL.

Locations of equipment / collaborators: The experimental facilities for this project are mainly located in EXSS labs. Additional characterization techniques will be available in the Materials and Chemistry Departments. Hall effect measurements will be performed remotely from ICL. The student will be collaborating with Dr Oki Gunawan (IBM) to plan and perform Hall measurements. A visit to IBM in Yorktown Heights, USA, may be considered for in person experiments.

Description of Ph.D. project in EXSS for Oct 2023 Entry

Project title:	**Microscopy and Spectroscopy of Topological Quantum Devices**		
Principal Supervisor:	Dr Malcolm Connolly	Project No:	MC_01
Email:	m.connolly@imperial.ac.uk		

Aims of the project: Probing how electrons behave in nanoelectronic devices has revolutionised our understanding of quantum systems and laid the foundations for a wide range of solid-state quantum technologies. This experimental PhD project involves probing a new class of quantum device whose electronic properties are governed by bandstructure topology. Electrons in these systems are forced to move along surfaces and edges where they avoid bulk noise and disorder, potentially improving the performance of quantum devices like qubits and metrological standards. The main aims of the project are:

1-Detecting Majorana zero modes in topological superconductors: Academic teams and technology companies such as Microsoft are developing a topological quantum computer using a special type of delocalised electron – a Majorana zero mode (MZM) - that forms at the ends of superconductor-semiconductor nanowires. MZMs have so far only been observed indirectly and never spatially resolved microscopically. Scanning gate microscopy, which uses the tip of an atomic force microscopic as a mobile local gate electrode, will be used to image their position as a function of magnetic field and gate voltage. Circuit quantum electrodynamics (cQED) will be used to spectroscopically detect MZMs embedded in superconducting qubits. The impact of this study is potentially very high as it will verify the spatial location of MZMs, one of their defining features.

2-Imaging topological gaps in magnetically-doped topological insulator devices: We will explore magnetically-doped V-VI compounds and take images of the spatial distribution of currents as two-dimensional surface states evolve into the one-dimensional edge channels. Capturing images at different carrier density and magnetic field should reveal precisely how this transition takes place, and by comparing with topography we can understand how it is affected by ionised surface and bulk impurities, edge disorder, and variations in crystal morphology (see https://magma.tmqs.lu/ for more details).

Techniques, activities, and equipment used: You will use a range of low temperature scanning probe microscopy techniques to image electrons at the nanoscale and verify these topological properties. You will also learn techniques such as circuit quantum electrodynamics, atomic force microscopy, scanning electron microscopy, electron-beam lithography and low-temperature transport measurements. Millikelvin in-operando scanning gate microscopy, electrical transport measurements, and microwave spectroscopy will be performed using the Quantum Science and Device Facility at Imperial.

Locations of equipment / collaborators: The Centre for Quantum Devices (QDev) at the University of Copenhagen and Juelich Forschungzentrum (FZJ) will participate in the fabrication of devices. Further fabrication will be performed at the London Centre for Nanotechnology.

Description of Ph.D. project in EXSS for Oct 2023 Entry

Project title:	**Antiferromagnets in superconducting spintronics**

Principal Supervisor:	Dr Niladri Banerjee	Project No:	NB_01
Email:	n.banerjee@imperial.ac.uk		
Other supervisors:	Lesley Cohen l.cohen@imperial.ac.uk		

Aims of the project:

Unconventional phases often arise when materials with dissimilar electronic and magnetic properties are placed in close proximity to each other. For example, a superconductor/ferromagnet (S/F) thin film hybrid structure can host unconventional superconductivity formed of parallel spin-paired electrons, the so-called triplet Cooper pairs, in contrast to the conventional spin anti-parallel singlet Cooper pairs. Due to the finite spin polarisation of triplet Cooper pairs, a dissipationless analogue of room temperature spin-based electronics (spintronics) is possible – a key step towards ultralow dissipation computing[1,2].

Although S/F hybrids have been extensively studied, very few experiments exist on the proximity effect between a superconductor and an antiferromagnet (S/AFM)[3]. A key advantage of AFM materials is its zero net magnetisation which avoiding vortex formation and demagnetising currents in superconductors. Furthermore, several interesting phenomena relevant to superconducting spintronics have been recently predicted in S/AFM hybrid structures like triplet superconductivity[4,5], topological nodal-point superconductivity[6] and anisotropic Josephson effect[7].

In this project, we will first systematically study the superconducting proximity effect of several AFM and establish key microscopic parameters like the coherence length and diffusion constant of Cooper pairs in the AFM. Based on these results, we will examine the nature of the Josephson coupling through these AFM and identify possible signatures of triplet Cooper pairs in S/AFM hybrids.

References:

1. https://www.nature.com/articles/nphys3242
2. https://physicsworld.com/a/a-cool-spin-on-supercomputers/
3. https://journals.aps.org/prb/pdf/10.1103/PhysRevB.68.144517
4. https://arxiv.org/pdf/2210.09325.pdf
5. https://www.nature.com/articles/s41563-021-01061-9
6. https://arxiv.org/abs/2208.12018
7. https://arxiv.org/abs/2108.06342

Techniques, activities, and equipment used:
You will learn and use thin film deposition and develop expertise in nano fabrication using standard optical and/or electron beam lithography and ion milling. You will also measure electronic and magnetic properties of the samples in low-temperature laboratory using cryogen-free systems. You will also work in close collaboration with our theoretical collaborators and might have the opportunity to develop some numerical models to explain your results.
Locations of equipment / collaborators: Nanofabrication and cleanroom facilities, Thin Film Technology Lab (Royce facilities) and low-temperature measurements in B815.

Description of Ph.D. project in EXSS for Oct 2023 Entry

Project title:	**Interfacial spin-orbit coupling based superconducting spintronics**

Principal Supervisor:	Dr Niladri Banerjee	Project No:	NB_02
Email:	n.banerjee@imperial.ac.uk,		
Other supervisors:	Lesley Cohen l.cohen@imperial.ac.uk		

Aims of the project:

Spin-based electronics (spintronics) which uses the electron spin for reading, writing and processing information plays a crucial role in modern computing and data storage technologies. However, spintronic devices still rely on dissipative charge currents as the source of spin currents and suffer from large heat dissipation. This problem could be potentially addressed using superconductors.

However, conventional superconductivity does not carry a net spin since it is formed of electron pairs with anti-parallel spins - the singlet Cooper pair. In the last decade several experiments[1,2] confirmed the existence of an exotic spin-triplet superconductivity in superconductor-ferromagnet (S/F) thin film hybrids which is formed of equal spin-paired electrons (triplet Cooper pairs) and carries a net spin. However, generating this triplet superconductivity usually requires S/F hybrid structures with complex magnetic textures.

Recently, we demonstrated that S/F hybrids with interfacial spin-orbit coupling and without complex magnetic textures can be used to generate triplets[3]. In addition to strikingly simplifying the thin film structures, presence of spin-orbit coupling (SOC) in S/F structures raises intriguing new possibilities such as magnetisation reorientation purely driven by superconductivity or magnetically tunable superconducting transistors[4,5].

This PhD project will explore the possibility to fabricate these SOC-based functional devices. For example, a key goal in the project will be to explore the fabrication of SOC-based spin triplet Josephson junctions and study the transmission of triplet supercurrents through materials with high SOC. These results will open up new paradigms in direct electrical control of the spin polarization of supercurrents mediated by SOC.

References:

8. https://www.nature.com/articles/nphys3242
9. https://physicsworld.com/a/a-cool-spin-on-supercomputers/
10. https://journals.aps.org/prb/abstract/10.1103/PhysRevB.97.184521
11. https://journals.aps.org/prb/abstract/10.1103/PhysRevB.99.134516
12. https://journals.aps.org/prb/abstract/10.1103/PhysRevB.100.224519

Techniques, activities, and equipment used:

You will learn and use thin film deposition and develop expertise in nano fabrication using standard optical and/or electron beam lithography and ion milling. You will also measure electronic and magnetic properties of the samples in low-temperature laboratory using cryogen-free systems. You will also work in close collaboration with our theoretical collaborators and might have the opportunity to develop some numerical models to explain your results.

Locations of equipment / collaborators:

Nanofabrication and cleanroom facilities, Thin Film Technology Lab (Royce facilities) and low-temperature measurement in B815.

Description of Ph.D. project in EXSS for Oct 2023 Entry

Project title:	**Artificial spin ice-based reprogrammable superconducting electronic devices**

Principal Supervisor:	Dr Niladri Banerjee	Project No:	NB_03
Email:	n.banerjee@imperial.ac.uk,		
Other supervisors:	Will Branford w.branford@imperial.ac.uk		

Aims of the project:

A geometrically frustrated system cannot simultaneously minimise all the pairwise interaction energy of its constituents. Such frustrated systems, where several degenerate configurations exist, are important for microelectronic memory and logic devices and can be engineered in artificial regular arrays of single domain nanomagnets arranged in honeycomb or square lattices[1]. These *artificial spin ice* systems have been investigated intensely in the last decade for applications in low-dissipative computing systems.

Similar analogues of these spin ice systems can be engineered using vortices in superconductors containing quantized magnetic flux in an array of nanostructured artificial pinning sites[2]. These superconducting flux-quantum ice systems have distinct advantages over spin ice displaying phenomena like glassiness and ice rule fragility that are absent in the spin ice systems.

However, neither of these systems have very high degeneracy, thus limiting its potential in data storage, memory and logic applications. Recently, hybrid superconductor-artificial spin ice systems have been developed which remarkably possesses a high degeneracy and fully magnetic field reprogrammable geometric frustration raising the intriguing possibility of low-power logic devices like the spin ice flux-quantum diode[3,4].

In this project, we will address some key questions which will enable us to make functional devices based on these hybrid systems:

- Can we tune the interaction strength between the superconducting vortices and magnetic charges by controlling the spin ice dimensions?
- Is it possible to use perpendicularly magnetized materials to engineer field-free vortex systems?
- What is the role of competing vortex states in determining the degenerate states of this hybrid system?

References:

1. https://www.nature.com/articles/nphys1628
2. https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.102.237004
3. https://www.nature.com/articles/s41565-018-0162-7
4. https://pubs.acs.org/doi/10.1021/acs.nanolett.0c04093

Techniques, activities, and equipment used:

Experimental: Thin film deposition, nano fabrication, magnetic force microscopy and low-temperature electronic transport and magnetic measurements.

Locations of equipment / collaborators: EXSS nanofabrication lab and cleanroom and functional magnetism laboratory (B815).

Description of Ph.D. project in EXSS for Oct 2023 Entry

Project title:	**Selective interfaces for mixed conducting perovskite solar cells and devices**

Principal Supervisor:	Dr Piers Barnes	Project No:	PB_01
Email:	piers.barnes@imperial.ac.uk		
Other supervisors:	Jenny Nelson jenny.nelson@imperial.ac.uk		

Aims of the project:

Metal halide perovskite semiconductors are a rapidly developing family of materials that can be solution-processed from earth-abundant elements while exhibiting optoelectronic properties reminiscent of classic inorganic semiconductors such as silicon or gallium arsenide. There is a huge research effort underway to deploy perovskites in solar cells where the current device efficiencies are on par with established silicon-based mainstream PV, demonstrating the quality and potential of the materials although stability challenges remain. In addition, researchers are exploring their application in many other areas including LEDs, transistors and multi-terminal device architecture, memristors and memdiodes, thermoelectrics, and optics.

An interesting property of metal halide perovskites is that in addition conventional semiconductor charge transport using free electrons and holes, they typically also contain a high concentrations of mobile ionic defects which carry charge and can redistribute within devices. The characterising and understanding the behaviour of these ionic charge carriers has been a focus of our group in recent years.

The project's core goal is to develop charge selective, trap-free junctions between neighbouring metal halide perovskite layers and perovskite , employing all-perovskite, lattice-matched, interfaces with the aim of eliminating interfacial defects while controlling ionic migration across them, to take the next step in device performance and stability. The proposed quasi-2D (layered perovskite) interfaces aim to create charge-selective molecular crystalline membranes using application-targeted cation molecules. This will allow unstable and costly device layers to be replaced, such as the typically expensive molecular hole transporters in solar cells. We also hope the resulting heterojunctions should help to enable development of a broad swath of electronic and optoelectronic devices more analogous to those based on conventional semiconductors, which can better utilise the outstanding properties and tunability of hybrid metal halide perovskite materials while taking advantage of their facile low-temperature processability.

Techniques, activities, and equipment used: The project will involve a combination of experimental and simulation work. The experimental work will involve device characterisation (and potentially fabrication) using transient and frequency domain optoelectronic characterisation techniques. Simulation will involve a combination of ab-initio quantum chemical calculations of the interface layers to inform device level drift-diffusion simulations.
Locations of equipment / collaborators: The project will involve close interaction with our collaborators at the University of Glasgow (Pablo Docampo and Graham Cooke) who will be developing the interlayer molecules and their incorporation in devices, and investigators at the University of Cambridge (Sam Stranks and Henning Sirringhaus) involved in device development and optoelectronic characterisation.

Description of Ph.D. project in EXSS for Oct 2023 Entry

Project title:	**Nonlinear physics with extreme fields and Peta-Hertz Optoelectronics**

Principal Supervisor:	Prof Rupert Oulton	Project No:	RF_O1
Email:	r.oulton@imperial.ac.uk		
Other supervisors:	Prof. John Tisch (QOLS)- john.tisch@imperial.ac.uk Dr. Mary Matthews (QOLS)- m.matthews@imperial.ac.uk		

Aims of the project:

When intense electromagnetic fields drive matter close to ionisation, Peta-Hz currents emerge generating extreme UV light and enabling resolution of physics on atto-second (10^{-18} s) timescales. To achieve the sufficiently intense optical fields, laboratory-based lasers are necessary, most of which are complicated bespoke systems: this is a barrier to wide-scale exploitation of this area of physics. This project explores extreme field opto-electronics essentially on a silicon chip. The primary excitement is the potential to break application barriers, eventually to enable portable and low-power implementations of extreme field physics. Moreover, the integrated opto-electronic setting enables the use of extremely high electrical fields in addition to optical fields. Uniquely, you will explore the mixing of both electrical and optical fields, both independently capable of ionising matter. This provides a unique opportunity to explore new physics.

The capabilities of such opto-electronic devices were demonstrated by our team with a publication in Science Magazine [*Science* **358** 1179 (2017)]. The technique has been honed over the past few years and is now ready to be deployed in this new area. The project will be co-supervised by Dr. Mary Matthews (Royal Society Fellow and Lecturer) who is an expert in extreme optical field and atto-second physics.

Techniques, activities, and equipment used

You will design and fabricate nanophotonic waveguide structures for optical experiments. The design process is conducted using Lumerical electromagnetic software. Nanofabrication will mostly involve electron beam lithography. You will test samples using our ultrafast laser laboratory. You will also have access to the ultrafast laboratories in QOLS to study the atto-second scale (Pet-Hz) responses of these devices.

Locations of equipment / collaborators

Nanofab lab, cleanroom, 1015 optics labs, QOLS group labs

Description of Ph.D. project in EXSS for Oct 2021 Entry

Project title:	**Nanofocusing tips for Scanning Near Field Optical Microscopy.**

Principal Supervisor:	Prof Rupert Oulton	Project No:	RFO-CP1:
Email:	r.oulton@imperial.ac.uk		
Other supervisors:	Prof. Chris Phillips chris.phillips@imperial.ac.uk		

Aims of the project:

The EXSS group (Prof. Phillips) is pioneering a Solid- State near field imaging technique, called scanning nearfield optical microscopy (SNOM), to look inside cells. It beats the diffraction limit of ordinary microscopy by a factor of ~3000, and the spatial resolution it gives (~3 nm), which rivals electron microscopy at a fraction of the time effort and cost. It has the potential to transform the biomedical sciences.

SNOM nanoscopes rely on a metallic "needle", to concentrate laser light at the point where tip and sample meet. Resolution is set by the needle's sharpness (< 2.5 nm across) rather than the wavelength. The convention in SNOM is to illuminate the needle from the side– shown schematically in Fig. 1a. However, this results in the illumination dominating the smaller signal from the tip-sample region.

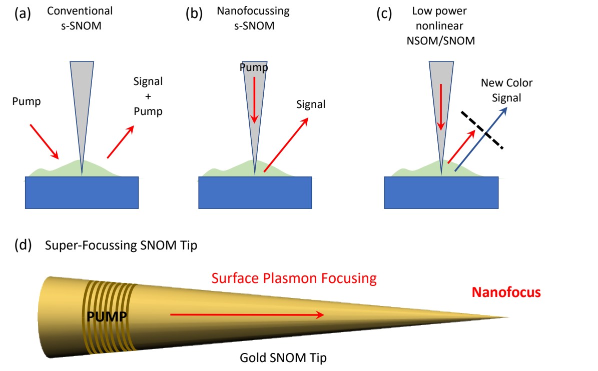

Fig 1. *Illustration of superfocusing and nonlinear s-SNOM nanoscope imaging. (a) conventional s-SNOM resulting in low signal to background noise. (b) superfocusing s-SNOM eliminates background. (c) nonlinear SNOM images new wavelengths of light generated at*

Low signal to background ratio means the technique has relatively low sensitivity and image acquisition speeds. In this project, you will eliminate the illumination background by using a "super-focussing" technique, where light is only delivered to the scanning needle's tip (Fig. 10b). Eliminating background noise boosts sensitivity to tip-sample absorption with considerably faster acquisition times. These features are imprtant for applying commercial SNOM nanoscopes to biomedical imaging. The dramatically improved sensitivity will provide better access to cellular ultrastructure than currently feasible.

the tip, further eliminating background. (d) Schematic of a super-focussing tip structure.

The project will also explore alternative contrast mechanisms for SNOM. E.g., strong nonlinear tip-responses generate new colours of light, which are modulated by the tip-sample interaction (Fig 1c). This allows pump light to be filtered, reducing noise.

Techniques, activities, and equipment used

You will fabricate superfocusing tips by modifying commercial high-resolution gold coated silicon scanning probe tips (needles) by etching optical gratings into them, as schematically shown in Fig 1d. This will require working with nanofabrication tools such as electron beam lithography, reactive ion etching and focussed ion beam milling. This will be conducted in our EXSS labs and clean-room. Some nanofabrication may be undertaken at the London Centre for Nanotechnology. You will test the performance of these elements in our ultrafast laser laboratory. Sample design and optimisation will be aided by computer simulations using Lumerical electromagnetic modelling software based on the Finite Difference Time domain method. You will be working as part of a larger team with the goal of integrating the nanofocusing tips into a commercial s-SNOM.

Locations of equipment / collaborators

Level 9 Blackett; Nanofab lab, cleanroom, 706 and 1015 optics labs, LCN

Description of Ph.D. project in EXSS for Oct 2022 Entry

Project title:	**Quantum Imaging with undetected photons**

Principal Supervisor:	Rupert Oulton, Chris Phillips	Project No:	RFO-CP2
Email:	r.oulton@imperial.ac.uk Chris.phillips@imperial.ac.uk		
Other supervisors:	Nathan Gemmel n.gemmell20@imperial.ac.uk		

Aims of the project:

Our team within the UK Quantum Imaging Hub is investigating the use of quantum correlated light sources for infrared imaging. This uses a method of imaging with undetected photons*, where an image is formed from photons that haven't interacted with the object in view at all! Apart from the intriguing fundamental aspect of this research, it has the practical advantage that high performance detectors in the visible, can be used to form images with other scientifically important, but technologically challenging, spectral regions – especially the mid infrared, which hosts the fingerprints of molecular vibrations.

The project involves developing nonlinear optics techniques to produce photon pairs bridging the visible and mid infrared (3-12 um wavelength), where vibrational absorption bands allow the chemistry of the object to be inferred. The results will be combined from other IR imaging methods in the group, including sub-wavelength s-SNOM images of cells and graphene devices, and our "Digistain" IR based cancer detection technology.

* Lemos et al "Quantum imaging with undetected photons" doi:10.1038/nature13586

Techniques, activities, and equipment used

Laser spectroscopy, nonlinear optics, spontaneous parametric down conversion, Tuneable Quantum cascade lasers, AFM, scanning scattering-near field optical microscopes (s-SNOM).

Locations of equipment / collaborators. Most equipment based in Physics Department at Imperial. Tissue specimens come from oncology and pathology collaborators mostly at Imperial Institutions. Quantum Hub collaborators at Glasgow and Bristol.

Description of Ph.D. project in EXSS for Oct 2023 Entry

Project title:	**Hot Electrons and Polaritons Science**

Principal Supervisor:	Rupert Oulton	Project No:	RFO-SM1
Email:	r.oulton@imperial.ac.uk		
Other supervisors:	Stefan Maier s.maier@imperial.ac.uk		

Aims of the project:

Optical nanostructures of metal or dielectric materials can support extremely large optical intensities of light. This is extremely useful for sensing applications – approaching single molecule level sensitivity. A side effect is the generation of heat due to absorption, which was thought to be a disadvantage but recently it was realised that this could enable chemical reactions. The absorption processes generate “hot” electrons that can significantly influence physical and chemical processes near interfaces; not (only) as a result of the high electric fields, but also from the transfer of these energetic electrons to adjacent molecules or materials. This paradigm now allows photo-chemical reactors for water splitting and CO_2 reprocessing, for example. At the same time, the interaction of the molecule with the metal particle, and with nanocavities in general, can profoundly alter the energetic states of the molecule, via the formation of a polariton.

The aim of this PhD project is to understand the physics and harness applications associated with such “hot” electron processes and molecular energy shifts, induced by photo-absorption in designer nanostructures constructed from a new breed of materials. This will open new paradigms in ultrafast control over nanoscale chemical reactions switchable with light, optically controlled catalysis, optical and electric processes in semiconductor devices induced by plasmonic hot-electrons, integration with two-dimensional materials such as graphene, as well as nanoscale metrology tools for temperature and field measurements.

Techniques, activities, and equipment Electromagnetic simulations and design, Optical Spectroscopy, ultrafast spectroscopy, Chemical Analysis.

Locations of equipment / collaborators.

Based at Imperial, but also in collaboration with the Universities of Bath, Manchester, Cardiff, King’s College London, and Monash University (Melbourne).

Imperial’s Physics Department Cleanroom, Glovebox, Nanofabrication facility and Laser Facilities.

Description of Ph.D. project in EXSS for Oct 2023 Entry

Project title:	**Time-varying metamaterials**

Principal Supervisor:	Prof Riccardo Sapienza	Project No:	RS_01
Email:	r.sapienza@imperial.ac.uk		
Other supervisors:	Prof. Stefan Maier- s.maier@imperial.ac.uk in collaboration with Prof. John Pendry- j.pendry@imperial.ac.uk		

Aims of the project:

You will study time-varying metamaterials, whose optical properties varies on femtosecond time scales. The project, joint between Prof. Stefan Maier, Prof John Pendry and Prof. Riccardo Sapienza, builds on the latest advances in nanophotonics, metamaterials and nonlinear optics, which gives powerful tools to control light-matter interaction at the nanoscale. Exploiting the nonlinear respose of semiconductors we will study temporal phenomena like the temporal Young slits diffraction, e.g. see one of our latest work https://arxiv.org/abs/2206.04362.

We are seeking an enthusiastic PhD student to undertake experimental research. The project involves design, nanofabrication and optical studies of nanostructures and metamaterials. The successful candidate should have a degree in physics, or material science. Independent thinking and multidisciplinary attitude are sought.

Techniques, activities, and equipment used.

You will use custom-built microscope, and an ultrafast spectroscopy setup.

Locations of equipment / collaborators. Lab B706

Description of Ph.D. project in EXSS for Oct 2023 Entry

Project title:	**Neuromorphic computation on physical neural networks**

Principal Supervisor:	Prof Riccardo Sapienza	Project No:	RS_02
Email:	r.sapienza@imperial.ac.uk		
Other supervisors:	Dr Will Branford- w.branford@imperial.ac.uk Dr Jack Gartside-j.carter-gartside13@imperial.ac.uk		

Aims of the project:

Neuromorphic computing, beyond the traditional van Neumann architectures of our personal computers, is poised to revolutionise the way we perform calculations, inspired by how the human brain works, and with better performances at a much lower energy cost.

You will implement neural networks on two different physical systems; arrays of magnetic particles and of nanoscale lasers, which are controlled by laser illumination. Both systems feature an array of coupled elements, where inputs can be encoded as a time sequence and the output measured as a frequency spectrum. The characteristic magnetic resonance, or lasing frequencies, have a non-linear dependence on the input sequence. In the nanomagnetic arrays it has already been shown that the frequency spectrum can provide numerous trainable outputs and so usefully act as physical reservoir in a neuromorphic computation (https://www.nature.com/articles/s41565-022-01091-7). The goal of the project is to transfer the same methodology to show useful reservoir computation from random lasing (https://www.nature.com/articles/s41467-022-34073-3) and to compare the performance of the two systems for different neuromorphic computation tasks, such as time-series predictions, handwriting and language recognition.

The project, joint between Prof. Riccardo Sapienza and Dr Will Branford, builds on the latest advances in nanophotonics and nanoscale magnetism, which gives powerful tools to control the state of matter optically and at the nanoscale.

We are seeking an enthusiastic PhD student to undertake experimental research. The project involves design, nanofabrication and spectroscopy studies. The successful candidate should have a degree in physics, material science or engineering. Independent thinking and multidisciplinary attitude are sought.

Techniques, activities, and equipment used.

In this particular project there will be a strong emphasis on taking utilising outputs from ferromagnetic resonance (FMR) and ultrafast optical spectroscopy data as the reservoir. Training on the reservoir outputs will be done with software machine learning (linear regression) methods. Cleanroom sample processing includes deposition of

metal films and lithography (optical, and e-beam). Structural studies involve imaging by optical, electron and magnetic microscopy and x-ray diffraction. Optical measurements will use custom-built lasing microscope and an ultrafast spectroscopy setup, Magnetic measurement techniques include FMR spectroscopy, vibrating sample magnetometry and magneto-optic Kerr effect (MOKE) spectroscopy.
Locations of equipment / collaborators. All in Blackett. B706, B815, nanofabrication laboratory.

Description of Ph.D. project in EXSS for Oct 2023 Entry

Project title:	**Solid-state nanoscale lasing on a graph**

Principal Supervisor:	Prof Riccardo Sapienza	Project No:	RS_03
Email:	r.sapienza@imperial.ac.uk		
Other supervisors:	Dr. Kirsten Moselund (EPFL, IBM Zurich)		

Aims of the project:

You will to develop unconventional laser to be integrated with silicon chip to power next generation optical computation technology. The project, at the interface between random lasing and advanced material science, builds on the latest advances in nanophotonics of disordered media, network theory and lasing, and aims at studying lasing in a mesh of nanoscale waveguide forming a physical graph. Preliminary work can be found here https://www.nature.com/articles/s41467-022-34073-3.

We are seeking an enthusiastic PhD student to undertake experimental research. The project involves design, nanofabrication and optical studies. The successful candidate should have a degree in physics, or material science. Independent thinking and multidisciplinary attitude are sought.

The project is in collaboration with Dr. Kirsten Moselund, in EPFL and IBM Zurich.

Techniques, activities, and equipment used. You will use custom-built lasing microscope in a state-of-the-art nanophotonic laboratory and nanophotonic fabrication tools, such as electron-beam lithography.
Locations of equipment / collaborators. B1016A, together with Dr. Kirsten Moselund, in EPFL and IBM Zurich (nanolaser fabrication and integration on chip)

Description of Ph.D. project in EXSS for Oct 2023 Entry

Project title:	**Theory of nanoscale lasing on a graph**

Principal Supervisor:	Prof Riccardo Sapienza	Project No:	RS_04
Email:	r.sapienza@imperial.ac.uk		
Other supervisors:	Dr. Raziman T V, Prof Mauricio Barahona (Imperial Mathematics)		

Networks for solid-state nanoscale lasers You will develop theory for unconventional network lasers to power next generation optical computation technology. The project lies at the interface between nanophotonics, semiconductor physics, and graph theory; and will be performed in close collaboration with experimenters who will realise the lasers designs. The project builds on the latest advances in nanophotonics of disordered media, network theory and lasing, and aims at studying lasing in a mesh of nanoscale waveguide forming a physical graph. Preliminary work can be found here https://www.nature.com/articles/s41467-022-34073-3.We are seeking an enthusiastic PhD student to undertake theoretical research. The project involves development of theoretical models, analysis of large systems using machine learning, and design of lasing networks. The successful candidate should have a degree in physics or applied mathematics. Independent thinking, multidisciplinary attitude, and collaborative spirit are sought. The project is in collaboration with Prof. Mauricio Barahona (Dept. of Mathematics).
Techniques, activities, and equipment used. You will use state-of-the-art theory tools, as for example netSALT that we have developed.
Locations of equipment / collaborators. Imperial Mathematics

Description of Ph.D. project in EXSS for Oct 2023 Entry

Project title:	**Rewritable Magnetic Nanostructures**		
Principal Supervisor:	Dr Will Branford	Project No:	WR_B1
Email:	w.branford@imperial.ac.uk		

Aims of the project: The functional magnetism group has a strong interest in the magnetic properties of nanostructured materials and devices. We have recently developed a method of writing any magnetic pattern we choose into magnetic nanostructured arrays that are usually called Artificial Spin Ice using a magnetic force microscope.[1,2] The aim of this project will be to fabricate artificial spin Ice structures and to use the writing technique to explore the possibilities for two new types of computation. One of these, known as a neural network, is a massively parallel computation based on the collective response of the whole network. The other, known as magnonics[3], relies on manipulating spin waves (magnons) within the nanostructures.[4] Ferromagnetic resonance, or FMR, is a standard tool used for probing spin waves and spin dynamics in ferromagnetic materials. FMR arises from the precessional motion of the magnetization of a ferromagnetic material in an external magnetic field.

[1] Controlling the network properties from different starting configurations.

[2] Measuring magnetic dynamics in different geometries.

[1] J. C. Gartside *et al. Sci Rep-Uk* **6**, 32864, (2016).
[2] J. C. Gartside *et al. Nat Nanotechnol* **13**, 53, (2018).
[3] D. Grundler. *Nature Physics* **11**, 438-441, (2015).
[4] T. Dion *et al. Phys. Rev. B* **100**, 054433, (2019).

Techniques, activities, and equipment used: PhD projects in the group will typically involve a mix of sample preparation, structural characterization, magnetic and transport measurements and micromagnetic simulations. Cleanroom sample processing includes deposition of metal films and lithography (optical, e-beam and focused ion beam). Structural studies involve imaging by optical, electron and magnetic microscopy and x-ray diffraction. Magnetic measurement techniques include FMR spectroscopy, vibrating sample magnetometry and magneto-optic Kerr effect (MOKE) spectroscopy. Electrical transport studies include magnetoresistance and Hall effect measurements. These measurements can be performed over a wide range of temperatures and magnetic fields.

Locations of equipment / collaborators: All in the Blackett Lab. Fabrication in the EXSS nanofabrication lab and cleanroom. Other measurements in the functional magnetism laboratory (B815). SQuID magnetometry in Spin-Lab (Materials department.)

Description of Ph.D. project in EXSS for Oct 2023 Entry

Project title:	**Writing wave-computing circuits in magnetic nanomaterials for magnonic and neuromorphic computing hardware**

Principal Supervisor:	Dr Will Branford	Project No:	WR_B2
Email:	w.branford@imperial.ac.uk		
Other supervisors:	Dr Jack Gartside j.carter-gartside13@imperial.ac.uk		

Aims of the project: The ballooning energy cost of computation is unsustainable, with more than 20% of global energy production forecast to be used for IT by 2030. Currently more the 75% of the world's data is stored magnetically and a key part of the problem is the 'von Neumann bottleneck' where ten times more energy is expended shuttling information between the processors and the hard drive as is used in the computation itself. using a magnetic processor offers a way to remove this bottleneck by collocating the data storage and logic processing functions. This is how the brain works and so it is often referred to as neuromorphic computing.

Spin waves in ferromagnets can transmit information without any physical exchange of particles between devices. This eliminates Joule heating, which is the primary sources of inefficiency in conventional computing. A quanta of spin waves is a magnon, and so computation with magnons is referred to as magnonics. We have found that in certain nanomagnetic arrays the spin wave spectrum is an excellent readout for neuromorphic computing. https://doi.org/10.1038/s41565-022-01091-7. In the development of magnonics is it much more attractive to explore devices where silicon technology struggles, than to make magnonic analogues of devices at whin silicon excels.

We have discovered that nanostructures where the individual nanomagnets can be either macrospins or vortices, then magnonic waveguides can be written to order, creating a testbed to explore device designs. https://doi.org/10.1021/acsnano.0c06894.

We have methods to write these structures with a magnetic scanning probe and with a nanofocused laser. Specific objectives include: (1) Fabricate bespoke arrays with macrospin/vortex coexistence and good waveguide properties. (2) Design and fabricate nanoscale microwave antenna structures for local measurement of the magnon power spectrum at the device output. (3) Write logic device structures in the magnetic state of the nanoarray with magnetic scanning probe and scanning laser. (4) Explore different magnonic circuit architectures for wave-computing and neuromorphic computing functions.

Techniques, activities, and equipment used: PhD projects in the group will typically involve a mix of sample preparation, structural characterization, magnetic measurements and simulations. Cleanroom sample processing includes deposition of metal films and lithography (optical, e-beam and focused ion beam). Structural studies involve imaging by optical, electron and magnetic microscopy and x-ray diffraction. Magnetic measurement techniques include FMR spectroscopy, vibrating sample magnetometry and magneto-optic Kerr effect (MOKE) spectroscopy. Electrical transport studies include magnetoresistance and Hall effect measurements. In this particular project there will be a strong emphasis local FMR spectroscopy data as the readout of the devices.
Locations of equipment / collaborators: All in the Blackett Lab. Fabrication in the EXSS nanofabrication lab and cleanroom. Other measurements in the functional magnetism laboratory (B815).

Description of Ph.D. project in EXSS for Oct 2023 Entry

Project title:	**Plasmonic control of Magnetic Metamaterials**

Principal Supervisor:	Dr Will Branford	Project No:	WR_B3
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Other supervisors:	Prof Rupert Oulton r.oulton@imperial.ac.uk		

Aims of the project: The functional magnetism group has a strong interest in the magnetic properties of nanostructured materials and devices. We have recently developed a method of writing any magnetic pattern we choose into magnetic nanostructured arrays that are usually called Artificial Spin Ice using a magnetic force microscope.[1,2] The aim of this project will be to fabricate artificial spin Ice structures, use the writing technique define starting states and plasmonic heating induce controlled relaxation of the magnetic structure. Structures of this type are interesting for neuromorphic computing hardware. Neuromorphic computing is a massively parallel computation based on the collective response of the whole network from a defined starting point. The nanostructures will be of a size such that the magnetic structure is static and can be written in ambient conditions, and then can be selectively heated by interaction with laser light to induce directed magnetic relaxation, which will be used as the computation process.

[1] Controlling the network properties from different starting configurations. [2] Exploring the evolution of the magnetic structure under laser illumination [1] J. C. Gartside *et al. Sci Rep-Uk* **6**, 32864, (2016). [2] J. C. Gartside *et al. Nat Nanotechnol* **13**, 53, (2018). [3] M. Pancaldi *et al. Nanoscale* **11**, 7656-7666, (2019). [4] J. H. Jensen *et al.* in *The 2019 Conference on Artificial Life.* 15-22.
Techniques, activities, and equipment used: PhD projects in the group will typically involve a mix of sample preparation, structural characterization, magnetic and transport measurements and micromagnetic simulations. Cleanroom sample processing includes deposition of metal films and lithography (optical, e-beam). Structural studies involve imaging by optical, electron and magnetic microscopy and x-ray diffraction. Magnetic measurement techniques include FMR spectroscopy, vibrating sample magnetometry and magneto-optic Kerr effect (MOKE) spectroscopy. Electrical transport studies include magnetoresistance and Hall effect measurements. These measurements can be performed over a wide range of temperatures and magnetic fields.
Locations of equipment / collaborators: All in the Blackett Lab. Fabrication in the EXSS nanofabrication lab and cleanroom. Other measurements in the functional magnetism laboratory (B815).

Description of Ph.D. project in EXSS for Oct 2023 Entry

Project title:	Nanomagnetic arrays for novel computation

Principal Supervisor:	Dr Will Branford	Project No:	WRB4
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Other supervisors:	Dr Rob Puttock, Dr Craig Barton		

Aim of the project: We have developed an all-optical nanomagnetic writing technique using a cheap, low-power (~2 mW) laser[1]. Unlike other opto-magnetic approaches, it requires no magnetic field, exotic materials nor powerful lasers - making it cheap, device-friendly & industrially-scalable. In parallel, we have developed the world-first nanomagnetic array neuromorphic computing scheme, providing low power neural-network functionality[2]. This proof-of-concept works well but neural network weight updates rely on a slowly varying magnetic field and lack single-nanomagnet resolution. Optical writing and reading now allows us to directly write network weights (nanomagnet states). This radically enhances operation speed & solves device compatibility issues, with huge potential for industrial uptake & impact. These unprecedented breakthroughs provide science-driven answers to spiralling global IT energy consumption. As a deep technology, we need expertise and

facilities for quantitative measurements to carefully establish the operating mechanisms and benchmark performance.

The project is use of the unique facilities at NPL in ultra-high resolution magnetic imaging (QSabr NV-diamond rig and quantitative magnetic force microscopy) and scanning thermoelectric microscopy (sThEM) to study nanomagnetic array samples from Imperial optimised for the laser writing and machine learning. The project could also involve nanofabrication, magnetic and magneto-optic measurements at Imperial. IAA funding will allow us to raise the TRL by benchmarking against memcomputing standards.

[1] Stenning, Kilian D., et al. "Low power continuous-wave all-optical magnetic switching in ferromagnetic nanoarrays." *arXiv:2112.00697* (2021).

[2] Gartside, J. C. et al. "Reconfiguranble training and reservoir computing in an artificial spin-vortex ice via spin-wave fingerprinting." *Nature Nanotech.* **17** 460 (2022).

Techniques, activities, and equipment used: This project will make use of the unique facilities at NPL in ultra-high resolution magnetic imaging (QSabr NV-diamond rig and quantitative magnetic force microscopy) and scanning thermoelectric microscopy (sThEM) to study nanomagnetic array samples optimised for the laser writing and machine learning. The project will also involve nanofabrication, magnetic and magneto-optic measurements at Imperial. Cleanroom sample processing includes deposition of metal films and lithography (optical, e-beam and focused ion beam). Magnetic measurement techniques include FMR spectroscopy, vibrating sample magnetometry and magneto-optic Kerr effect (MOKE) spectroscopy. Electrical transport studies include magnetoresistance and Hall effect measurements. These measurements can be performed over a wide range of temperatures and magnetic fields.

Locations of equipment / collaborators: Work both in the Blackett Lab and at the NPL campus in Teddington. Fabrication in the EXSS nanofabrication lab and cleanroom. Magnetization and imaging measurements in the functional magnetism laboratory (B815). SQuID magnetometry in Spin-Lab (Materials department.) NV-diamond and sThEM imaging at NPL.