

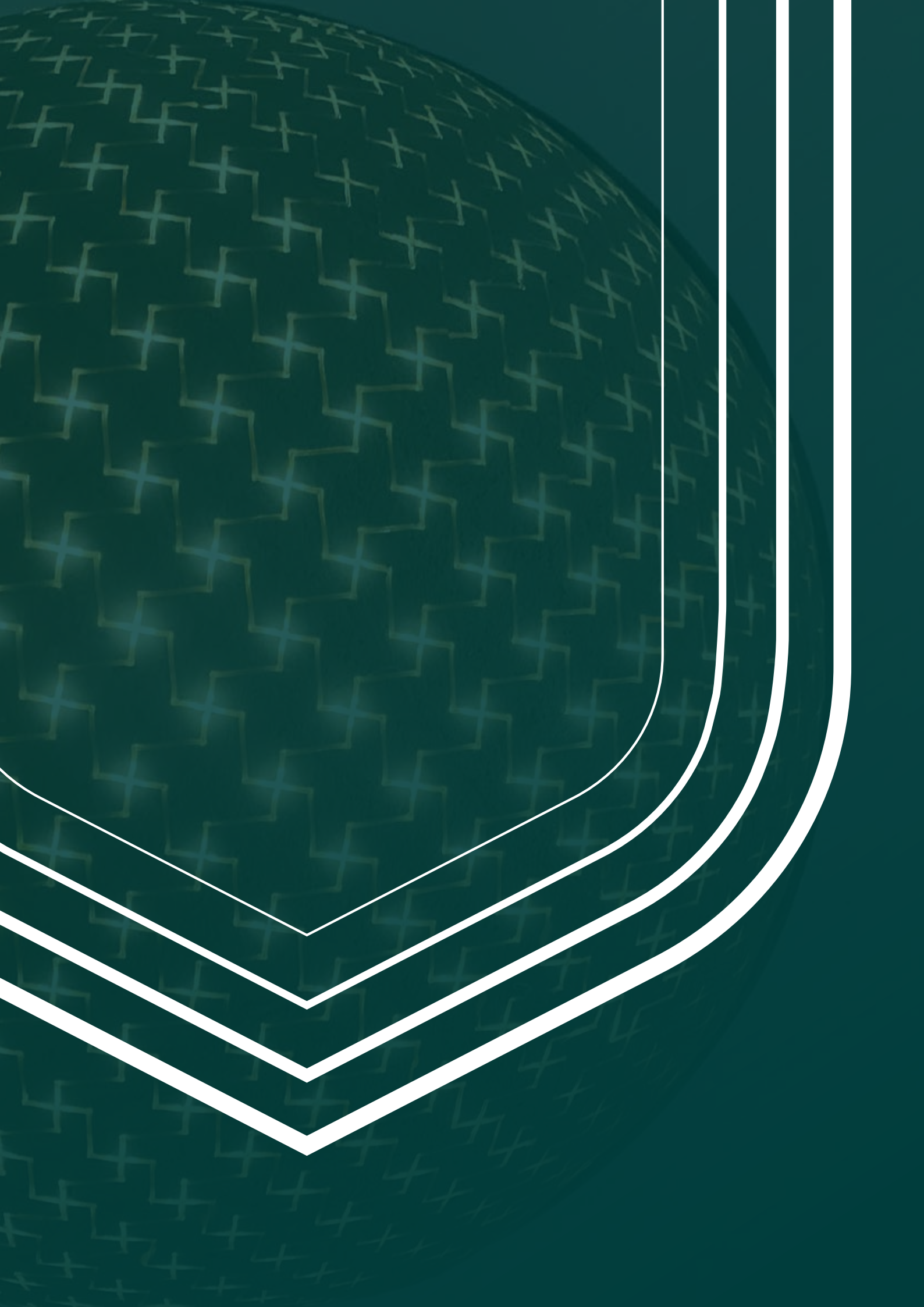


Advanced Materials

Connecting Industries with Physics and Engineering



Exeter
INNOVATION



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Overview

This Brochure highlights the contribution of our world-leading R&D across the theme of Advanced Materials. Over the years, we have created a strong reputation through our work with companies to develop new materials, improve methods of manufacture, and optimise new devices for various applications. We work across six major areas, and we are one of the two Universities that lead the UK's Metamaterials Network.

Advanced Materials for Bioengineering

The University of Exeter has vast expertise across the theme of Advanced Materials for Bioengineering. Research activities are embedded in today's engineering challenges and future engineering vision covering expertise in bioengineering, computational mechanics, musculoskeletal systems and wearable electronic devices.

Image-based Numerical Modelling of Knee Joint

The Problem:

Osteoarthritis (OA) has become a common ailment in joints, usually caused by gradual loss of cartilage or a previously sustained injury. An estimated 10 million people (6 million women, 4 million men) in the UK have OA, with an estimated 5.4 million people affected by knee OA. About 350,000 people are diagnosed with OA each year¹. In 2019, about 528 million people worldwide were living with OA, an increase of 113% since 1990². Osteoarthritis causes a deterioration of the bone structure and the surrounding soft tissue, resulting in severe pain and reduction of movement in the affected joint. This pain can be attributed to the entire weight of the body being repeatedly transferred through the damaged knee during walking. The deterioration of the joint and the cartilage leads to increased friction between the bones. In most cases of OA, the damaged cartilage/ligament cannot support the whole weight of the patient and the resulting pain can severely restrict mobility which, in turn, has significant implications on patients' general health. There are various engineering solutions to help with knee OA. To identify appropriate interventions, it is important to understand the loads applied to the knee joint and their effects on the mechanical behaviour of the different components of the knee joint.

Our Solution:

We have developed a framework for image-based three-dimensional finite element modelling of stresses and strains in different parts of the knee joint and comparing the performance and stress concentrations in OA and healthy knees. A complex bio-realistic model of a knee joint was constructed from medical MR images of a subject with a healthy knee. The images were segmented to define the boundaries of the bones and soft tissues using ScanIP software (Synopsys, Mountain View, USA). The segmented parts were then exported and assembled to form the three-dimensional FE model of the knee joint. The model was initially constructed to examine the properties and function for the healthy knee conditions and it was then modified to represent OA conditions. The material properties of the model were changed and the thickness of certain components of the model was altered to create the OA conditions, as OA occurs due to the thinning of the cartilage. The developed model provides a useful tool to study the consequences of OA conditions and design appropriate engineering interventions.

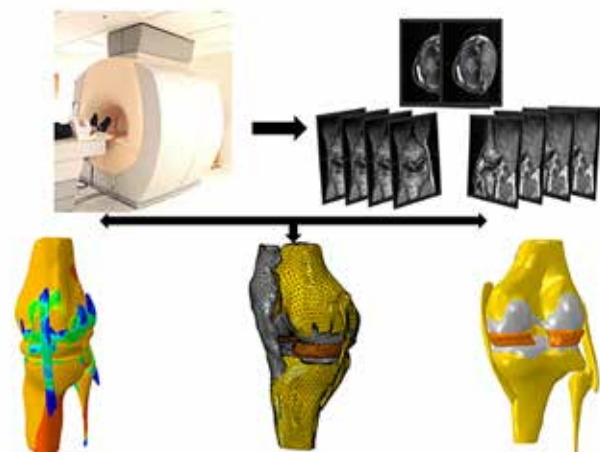


Image-based modelling framework.³

Figure reproduced from "Thienkarochanakul, K., Javadi, A.A., Akrami, M. *et al.* (2020) Stress Distribution of the Tibiofemoral Joint in a Healthy Versus Osteoarthritis Knee Model Using Image-Based Three-Dimensional Finite Element Analysis. *J. Med. Biol. Eng.* 40, 409–418, <https://doi.org/10.1007/s40846-020-00523-w>."

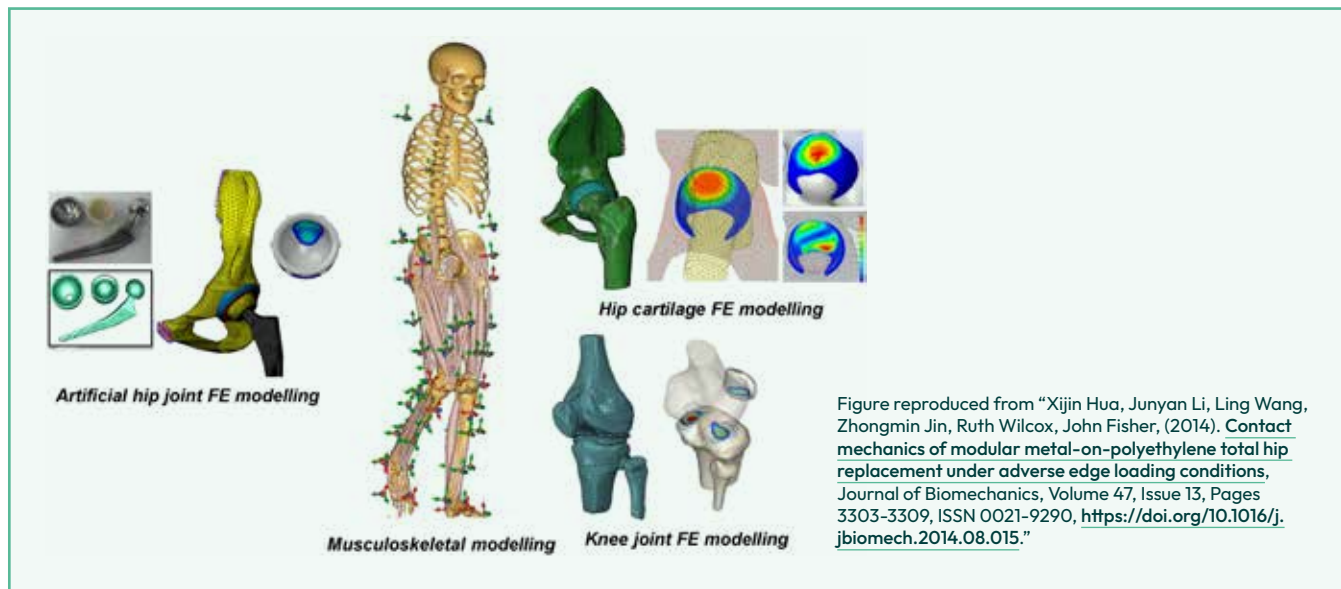
¹ Versus Arthritis 2023; ² WHO Report [who.int/news-room/fact-sheets/detail/osteoarthritis](https://www.who.int/news-room/fact-sheets/detail/osteoarthritis); ³ Medical and Biological Engineering, 40: 409–418, (2020).

The Musculoskeletal Model

Research within the University of Exeter encompasses computational biomechanics, specialising in the innovative modelling and simulation of biomaterials. We employ musculoskeletal modelling to deeply understand muscle forces, their functionality, and the underlying causes and implications of disorders, alongside the study of soft tissues such as ligaments. Utilizing finite element analysis, we explore the biomechanics of bones, cartilage, and artificial joints, focusing on their responses to stresses, strains, and deformation. This exploration is instrumental in driving forward the frontiers of biomaterial science. Our work is also at the cutting edge of integrating computational simulation with state-of-the-art optimization and 3D printing technologies. This integration stands at the forefront of developing tissue-like materials, metamaterials, and next-generation medical devices. Furthermore, our research is pivotal in leveraging computational modelling for the prevention and rehabilitation of musculoskeletal disorders, marking a substantial impact on the field of advanced biomaterials and medical engineering.

Case study

The articular cartilage in the lower limb joints, such as the hip and knee, is characterized as a bi-phasic material, consisting of a solid phase and a fluid phase. Typically, the fluid phase bears the majority of the joint load during human activities. This material exhibits time-dependent nonlinear mechanics in response to physiological loading encountered during these activities. A thorough understanding of the cartilage's time-dependent behaviour under physiological loads is crucial for grasping the onset of joint pathologies and informing clinical treatments. This project was designed to develop a multiscale computational model of the body and to utilize this model to investigate the time-dependent response of the articular cartilage in the hip joint to physiological conditions during seven activities of daily living (i.e. normal walking, squat, ascending stairs, descending stairs, standing up, and sitting down). The multiscale model includes a musculoskeletal model of the body for analysing muscle forces and internal joint loading, and a finite element model of the hip joint and articular cartilage for predicting the time-dependent response to physiological conditions. The findings reveal that for all activities considered, interstitial fluid pressure within the articular cartilage supports more than 80% of the load. The maximum values of peak contact pressure and peak fluid pressure throughout the entire cycle show an initial increase followed by stabilization over time. The predicted internal loading within the hip joint reaches 2871N during stair descent, and the maximum contact stress within the cartilage is predicted at 4.41MPa during squatting activities, for a subject weighing 76 kg.



Wearable Self-Powered Biosensors Based on 2D Materials on Textile Platforms

Overview:

This research explores the development of wearable biosensors that are integrated into textile platforms while being self-powered by harnessing energy from the wearer's movements. Recent breakthroughs in healthcare rely on integrating state-of-the-art self-powered sensing technologies into textiles, notably with triboelectric nanogenerators (TENG). TENGs are devices that convert biomechanical energy, like walking or

movement of various body parts, into electricity. These devices, more eco-friendly than battery-powered ones, are ideal for wearable health monitoring.

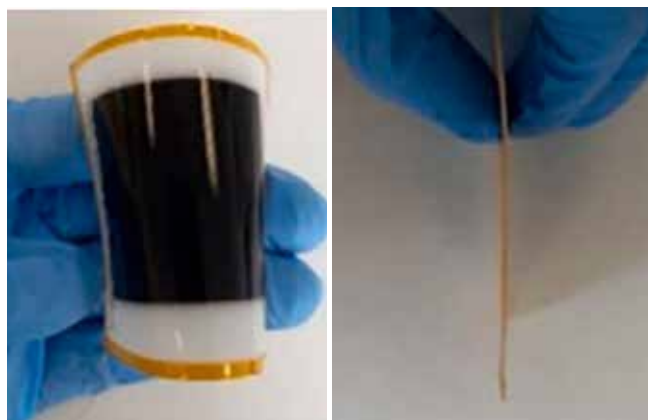
Our research focuses on designing flexible, lightweight TENG biosensors using graphene and 2D materials, ensuring the required electrical performance and resilience.

Case study: Wearable electronic devices on textile substrates using graphene

Aim: To move away from bulky and rigid portable electronics devices and achieve truly wearable technology, it is important to use textiles as substrates rather than simply sticking some piece of hardware to them. However, textiles substrates bring an array of additional challenges due to their flexibility and inherently rough structure. Therefore, using advanced materials and developing suitable coating techniques is paramount.

Approach: Using graphene as a flexible electrode, we have successfully coated different types of graphene onto textile fibres and fabrics. Adapting the manufacturing and transfer routes for graphene (e.g. chemical vapour deposition, graphene nanoplatelets, spray coating) to the type of surface coated allowed for the achievement of conductive textiles to be used for a range of devices. The integration with textiles offers comfort and flexibility, making these biosensors ideal for continuous monitoring of health parameters in real-time.

Results: We have fabricated electroluminescent devices, touch sensors, temperature and humidity sensors using textile fibres, both as arrays and single-fibre devices. Triboelectric nanogenerators, capable of harvesting mechanical energy from human motion have been fabricated on using woven fabrics, also showing sensing capabilities. These sensors, integrated into textiles, offer stable performance and sensitivity to monitor human movement, making them suitable for bioelectronics, robotics, and healthcare. Additionally, we are exploring 2D materials for textile wearable sensors for detecting disease biomarkers in sweat, showing promise for personalized healthcare i.e. these devices have the potential to be used as self-powered wearable sensors for biomedical applications, including remote healthcare, in monitoring vital signs and tracking joint motion.

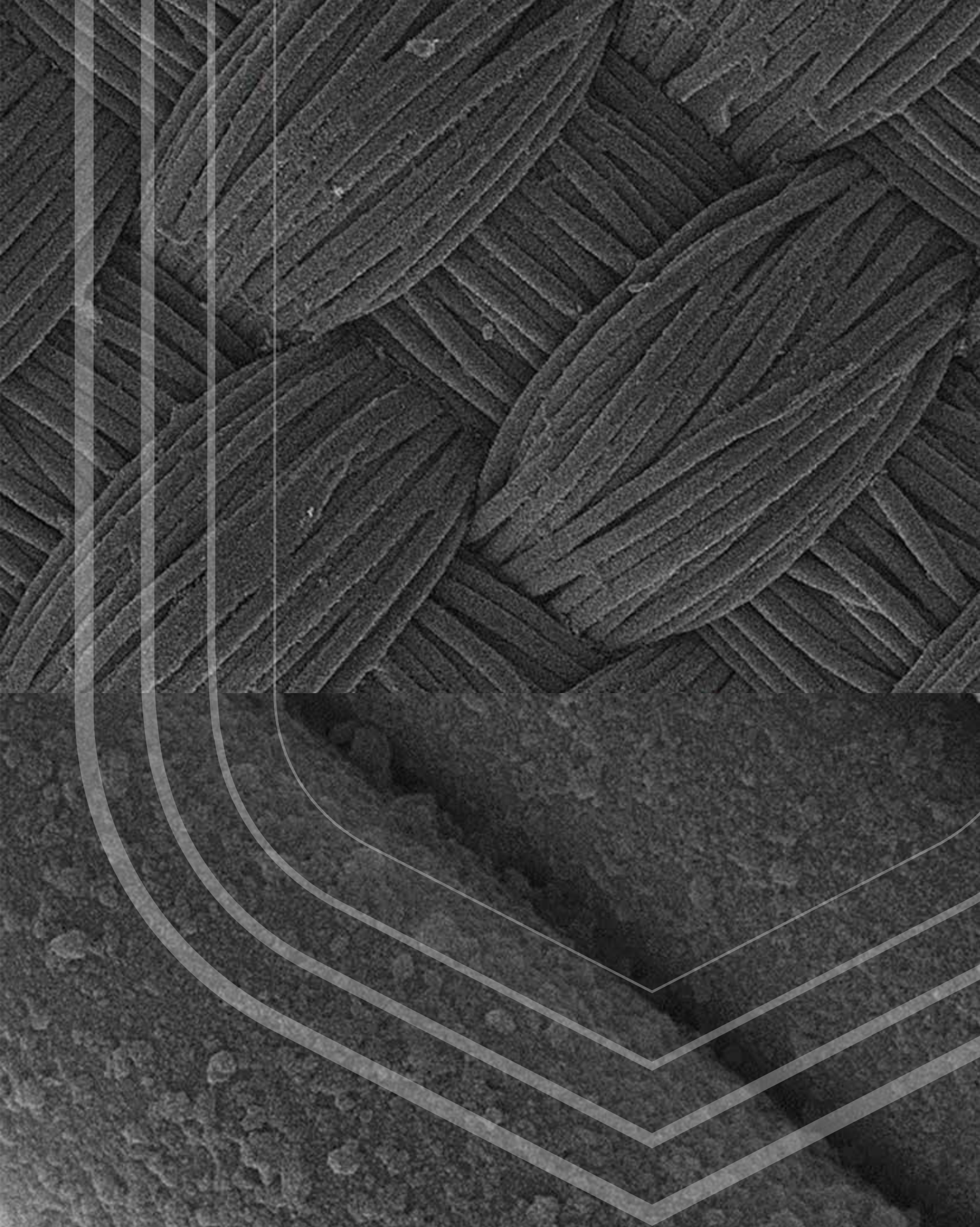


Photos of TENG device based on graphene on textile showcasing its flexibility and ultra-low thickness from bent and cross-section angles.

Figure reproduced from "Kavya Sreeja Sadanandan, Zakaria Saadi, Conor Murphy, Ineta Griksaitė, Monica F. Craciun, Ana I.S. Neves (2023). Fabric-based triboelectric nanogenerators with ultrasonic spray coated graphene electrodes, *Nano Energy*, Volume 116, 108797, ISSN 2211-2855, <https://doi.org/10.1016/j.nanoen.2023.108797>."

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SEM images of polyester spray-coated with graphene nanoplatelets, at a 200× (top) and 5000× (bottom) magnifications.

Figures reproduced from "Kavya Sreeja Sadanandan and Agnes Bacon and Dong-Wook Shin and Saad F R Alkhalifa and Saverio Russo and Monica F Craciun and Ana I S Neves, (2020), **Graphene coated fabrics by ultrasonic spray coating for wearable electronics and smart textiles**, Journal of Physics: Materials, IOP Publishing, 4, 1, 014004, DOI: [10.1088/2515-7639/abc632](https://doi.org/10.1088/2515-7639/abc632)."

2D Materials and Quantum Technologies

The quantum realm drives the future of electronics, emphasizing size reduction, performance enhancement, and functional integration in single devices. We are leading the exploration of this quantum frontier in nano-systems, operating on just one or a few atoms-thick systems, which demands a departure from traditional macroscopic device science, as it unlocks new physical properties grounded in quantum mechanics.

Case study

The University has developed a new way to control the behaviour of certain quantum particles called excitons in thin layers of 2D materials. Excitons in 2D materials, like MoS₂, WS₂, are extremely important for future quantum technology as these materials are kept stable at room temperature, or higher. Our research showed that we can drastically control how these excitons behave in a single layer of 2D material, just by changing the surroundings. These findings are important for developing new types of solar cell materials that are only a few atoms thick, as well as opening new opportunities for the development of quantum technologies that work at room temperature, bringing futuristic quantum capabilities into our everyday lives.

Two-dimensional Materials for Quantum Photonic Technologies

Quantum technologies have the potential to impact on almost all aspects of our lives; quantum communication provides unbreakable security to protect our personal and financial data; quantum sensing can provide security to navigation and unlock new medical diagnostic techniques; and quantum computing can profoundly change our approach to drug development, logistics and the discovery of new materials. These technologies can all be realised using quantum photonics, which relies on the generation, control, and detection of single photons.

However, to deliver on this promise, there is a pressing need for new underpinning materials, components, and devices and this is the focus of the Exeter Quantum Nanophotonics group.

We are exploring two-dimensional (2D) materials as a building block for single photon sources^{1,2}, super-resolution imaging³ and quantum sensors^{4,5,6}. A 2D material is one which can exist in a single atomic layer, with its atoms arranged in a two-dimensional structure. Several hundred 2D materials have been isolated to date, many of which have very different properties compared to their bulk counterparts. Furthermore, 2D materials can be stacked together using simple techniques, to form heterostructures with atomically precise interfaces, providing a wealth of opportunity to explore novel physical phenomena and realise solutions across a wide range of applications. Several 2D materials can host artificial atoms, formed at defects in the crystal lattice. The opportunity to integrate these artificial atoms into 2D heterostructure devices, and with high performance integrated photonics, offers a unique opportunity to develop novel quantum-optoelectronic devices.

Single Photon Sources

A single photon source is an optoelectronic device that can generate a single photon on demand. The photons must be generated at a high repetition rate and to be used in many quantum protocols they must be indistinguishable (have the same wavelength, polarization and temporal and spatial extent). Two of the major challenges in the development of solid state single photon sources are the deterministic fabrication of a single photon emitter and device integration that enables electrically driven operation. At Exeter, we have addressed this challenge with a device geometry consisting of gold pillars embedded in a van der Waals heterostructure of graphene, hexagonal boron nitride, and tungsten diselenide (see Fig. 1(a))¹. The role of the gold pillar is twofold: (1) it induces strain that leads to localised single photon emitters at a predetermined spatial position (Fig. 1(b); and (2) it acts as nanoscale contact for charge injection, which allows electrically driven single photon emission (Fig. 1(c)).

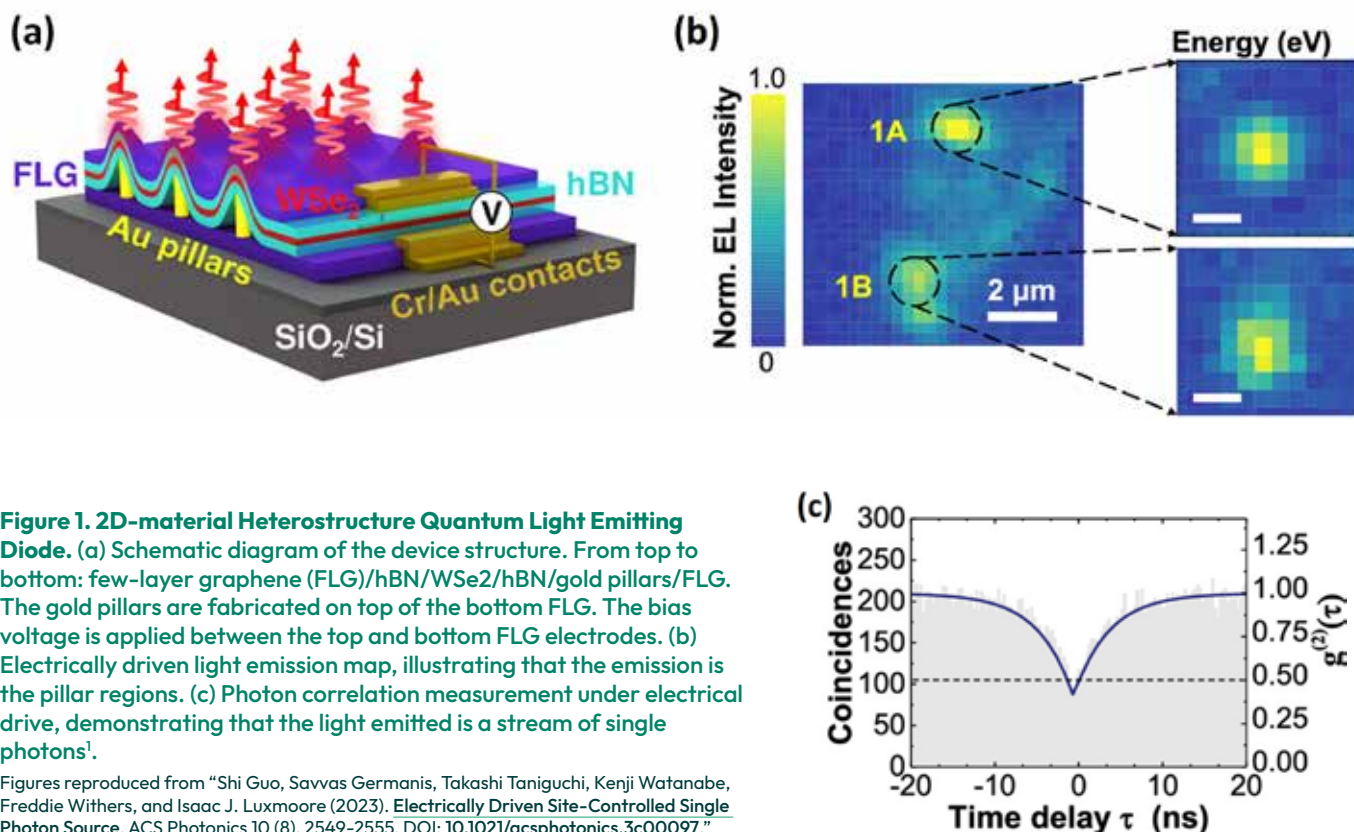


Figure 1. 2D-material Heterostructure Quantum Light Emitting Diode. (a) Schematic diagram of the device structure. From top to bottom: few-layer graphene (FLG)/hBN/WSe₂/hBN/gold pillars/FLG. The gold pillars are fabricated on top of the bottom FLG. The bias voltage is applied between the top and bottom FLG electrodes. (b) Electrically driven light emission map, illustrating that the emission is the pillar regions. (c) Photon correlation measurement under electrical drive, demonstrating that the light emitted is a stream of single photons¹.

Figures reproduced from "Shi Guo, Savvas Germanis, Takashi Taniguchi, Kenji Watanabe, Freddie Withers, and Isaac J. Luxmoore (2023). Electrically Driven Site-Controlled Single Photon Source, ACS Photonics 10 (8), 2549-2555, DOI: 10.1021/acsp Photonics.3c00097."

Quantum Sensing Platform

Precision measurement underpins all areas of science and technology and novel sensors that push the fundamental limits of accuracy and precision are required in applications ranging from nano-electronics to medical imaging. In nanoscale sensing the sensor must fulfil three main requirements: (1) the sensor must be small compared to the object that is under investigation; (2) the geometry of the sensor must allow it to be placed near the object under investigation; and (3) the sensor must be highly sensitive to the quantity it is sensing. Sensors based on colour centre defects

in wide bandgap semiconductors can fulfil these requirements, thanks to their atom-like electronic transitions and a spatial extension on the scale of the atomic lattice. We are investigating defects in the 2D semiconductor hBN, which have magnetic field dependent photoluminescence. This makes these defects an ideal candidate for nanoscale magnetometry as the 2D nature of the host material offers the unique advantage that the sensor can be brought very near to, or even be embedded within, the target system.

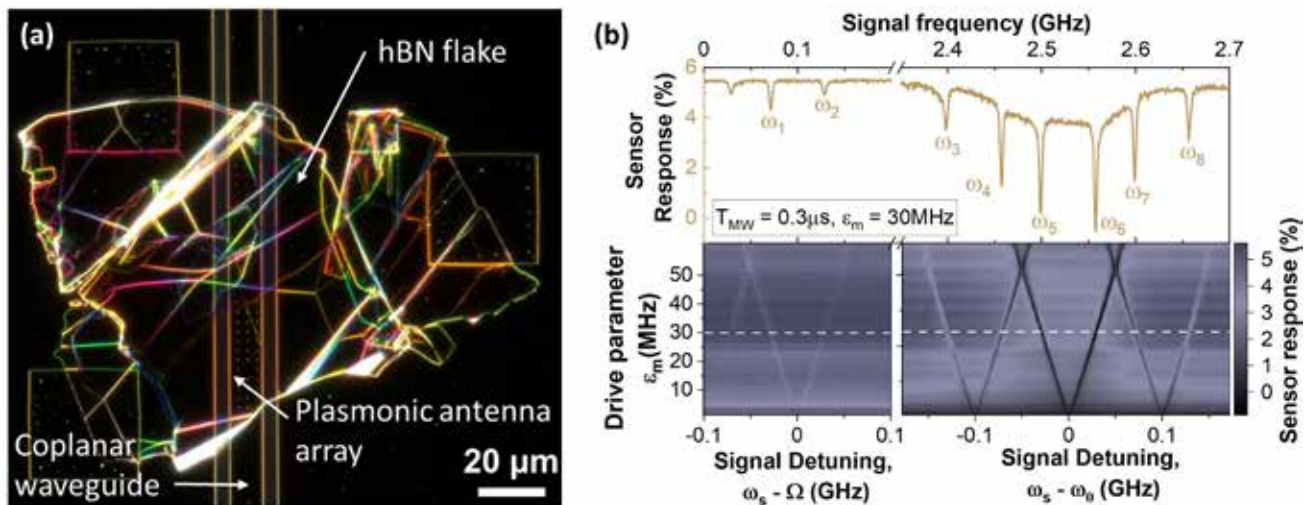


Figure 2. 2D-material Quantum Sensing Platform. (a) Dark-field microscope image of an hBN flake transferred onto a microwave co-planar waveguide. Plasmonic antennas on top of the hBN layer enhance the fraction of photoluminescence collected, thus improving the measurement sensitivity. (b) The defect photoluminescence intensity is sensitive to the applied microwave field and the frequency/amplitude of a signal in the MHz to GHz frequency range, thereby enabling the detection of an unknown signal.

Figures reproduced from "Patrickson, C.J., Baber, S., Gaál, B.B. *et al.* (2024) High frequency magnetometry with an ensemble of spin qubits in hexagonal boron nitride, npj Quantum Inf 10, 5. <https://doi.org/10.1038/s41534-023-00796-4>."

Figure 2 presents an overview of our work to develop an AC magnetic field sensor using an ensemble of negatively charged boron vacancies in an hBN flake. As shown in Fig. 2(a), the flake is positioned on top of a gold coplanar waveguide¹. This allows excitation of defects in the flake both with visible radiation from a

focused laser beam and microwave radiation, via the waveguide. This combined optical and microwave excitation enables us to sense small alternating magnetic fields and to determine their frequency and amplitude (Fig. 2(b))^{5,6}.

References:

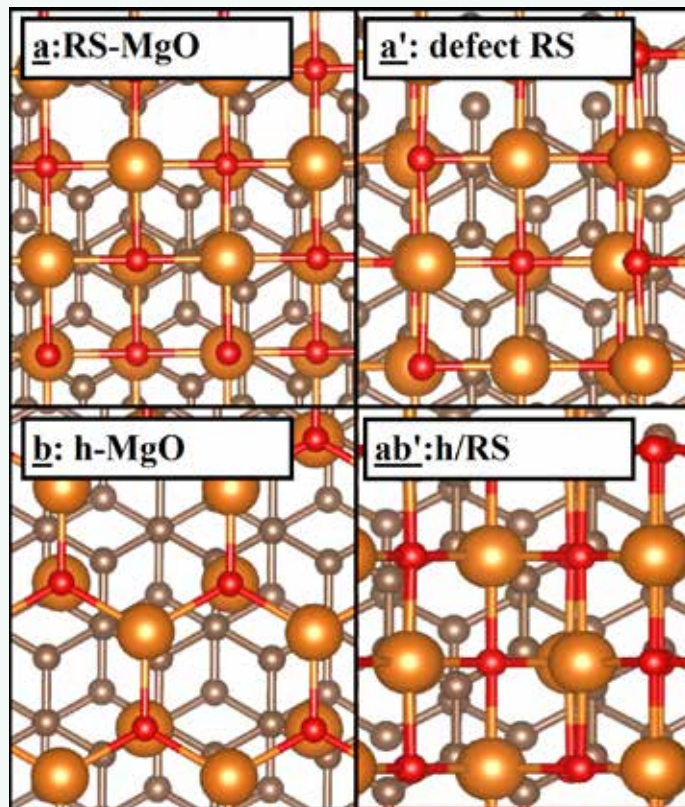
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Case study: Predicting the structure of interfaces; the join between materials

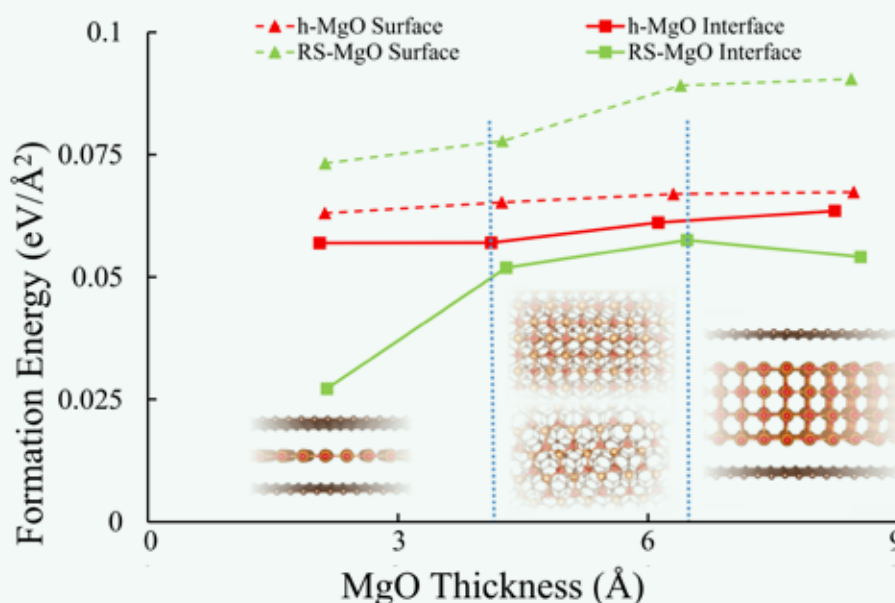
Aim: “The interface is the device” Nobel laureate Herbert Kroemer. The joins between components is termed the interface and dictates the properties of a device. Often in most devices and systems the limiting factors are the interfaces. By predicting theoretically the atomic structure of the interface and how this depends on its conditions of manufacture, we can optimise and improve performance of devices dramatically.

Challenges: Predicting the join between two materials at the atomic level is a highly challenging task, due to multiple configurations, rogue particles, stray electric and strain fields and other effects. By predicting what materials form at these interfaces, both better joints can be developed, but also new materials can be found, which were previously impossible under normal conditions. Researchers at Exeter have developed one of the first tools, RAFFLE, capable of optimising and predicting the structure of interfaces using a combination of theoretical physics and machine learning. This allows accurate prediction of the properties of electrical contacts, heterojunctions, solar panels and thermoelectric devices.

Using our RAFFLE technique, we can show how the material structure depends on how thick the join between the Magnesium oxide and graphite layers is.



Examples of the difference configurations of how Magnesium oxide bonds with graphite.



Figures reproduced from “Pitfield J, Taylor NT, Hepplestone SP. (2024) Predicting Phase Stability at Interfaces, *Physical Review Letters*, volume 132, no. 6, article no. 066201, DOI:10.1103/physrevlett.132.066201.”

Advanced Materials in Energy

We are investigating the underpinning science of 2D materials for applications in energy, with 2D materials attracting global interest for their potential to provide sustainable solutions to growing energy demands. Our research spans across multiple themes including hydrogen, batteries storage, energy harvesting and photovoltaics.

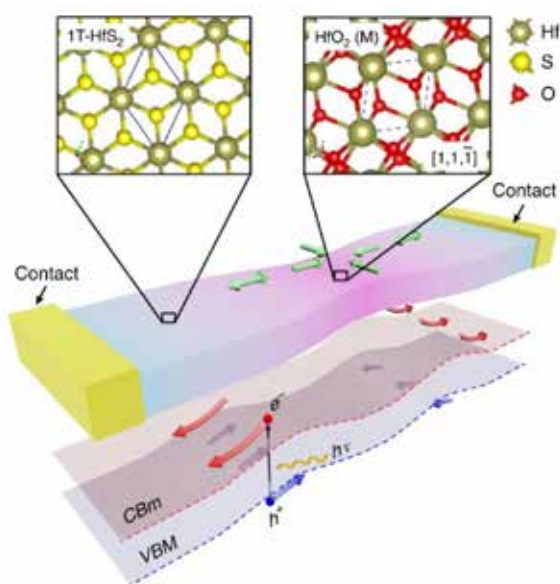
2D Energy materials

In the area of photovoltaics we demonstrated the development of the first electron funnel on a chip for the next generation of efficient solar cells. This technology could unlock new ways of ‘funnelling’ the sun’s energy more efficiently directly into solar panels.

Watch our video: youtu.be/apl-hYy4EWc



As electrodes for solar cells, we demonstrated the potential of FeCl₃ functionalised graphene for work function matched transparent electrodes in photovoltaic devices. We also showed an improved stability of organic photovoltaic devices when using FeCl₃ functionalised graphene electrodes as compared to Indium Tin Oxide.



In this study, we explore how bending the 2D material HfS₂ affects the flow of electrical charges. We use a special method to compress the HfS₂ in the middle while leaving the edges stretched. This compression creates a sort of ‘funnel’ effect, where charges are pushed towards certain areas, changing how the material conducts electricity. The diagram shows how this device works, with the compression highlighted in the centre of the HfS₂ channel. As a result, the bandgap, which determines how easily electrons can move through the material, is changed in different parts of the device.

Figure reproduced from “De Sanctis, A., Amit, I., Hepplestone, S.P. *et al.* (2018) Strain-engineered inverse charge-funnelling in layered semiconductors, *Nat Commun* 9, 1652, <https://doi.org/10.1038/s41467-018-04099-7>.”

Triboelectric nanogenerator energy harvesting devices

In the area of triboelectric nanogenerator energy harvesting devices, we developed the integration of high-quality graphene films obtained from scalable water processing approaches as electrodes, opening new possibilities for self-powered flexible and wearable electronics. We also used solution processed graphene both as an electrode and active triboelectric layer and showed an enhancement in the power output by 40 times compared to standard metal electrodes. We demonstrated the use of 2D materials heterostructures in energy harvesting including photovoltaic devices using graphene electrodes and WS₂–MoS₂ photo-active layers. Our latest developments in this area include a novel textile-integrated triboelectric nanogenerator capable of sensing and harvesting low-frequency acoustic energy. These capabilities are enabled by a unique combination of sustainable materials such as beeswax as a triboelectric layer and graphene-based electrode, endowing multiple functionalities. Specifically, our device can sense ground-borne sounds in the 10–200 Hz frequency range, detect human voices, recognise human emotions, and harvest energy from environmental noise and vibrations. Additionally, the dynamic molecular interactions and the hydrophobic nature of the triboelectric layer provide intrinsic thermal healing, water-repellent, and self-cleaning features, ensuring device functionality in bending and humidity environments.



A textile-integrated triboelectric nanogenerator using beeswax as triboelectric layer and graphene as electrode.

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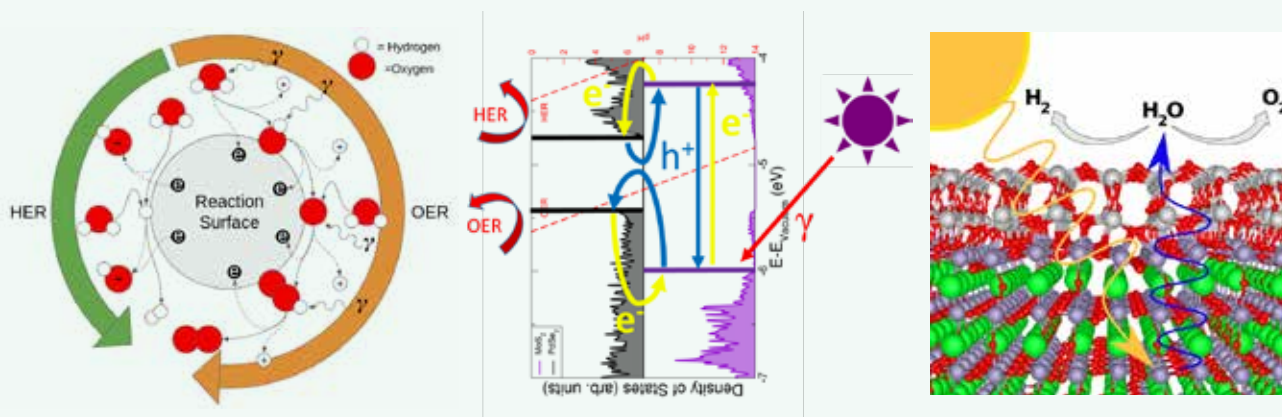
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Advanced Materials for Hydrogen and Renewables

Case study: Optimising water splitters using overlayer coatings

Aim: Converting sunlight into a useful fuel, such as hydrogen has long been a goal. A photocatalyst enables this process by allowing water to break down into hydrogen and oxygen gas on the surface using sunlight. Finding or designing an advanced material that could carry out this process would allow for cheap and ready generation of hydrogen fuel.



- (a) The reaction path ways for splitting water into oxygen (red) and hydrogen (white).
- (b) A demonstration of how structuring the surface can drive electronic carriers (the electron and hole) to the surface to carry out the reaction steps in (a).

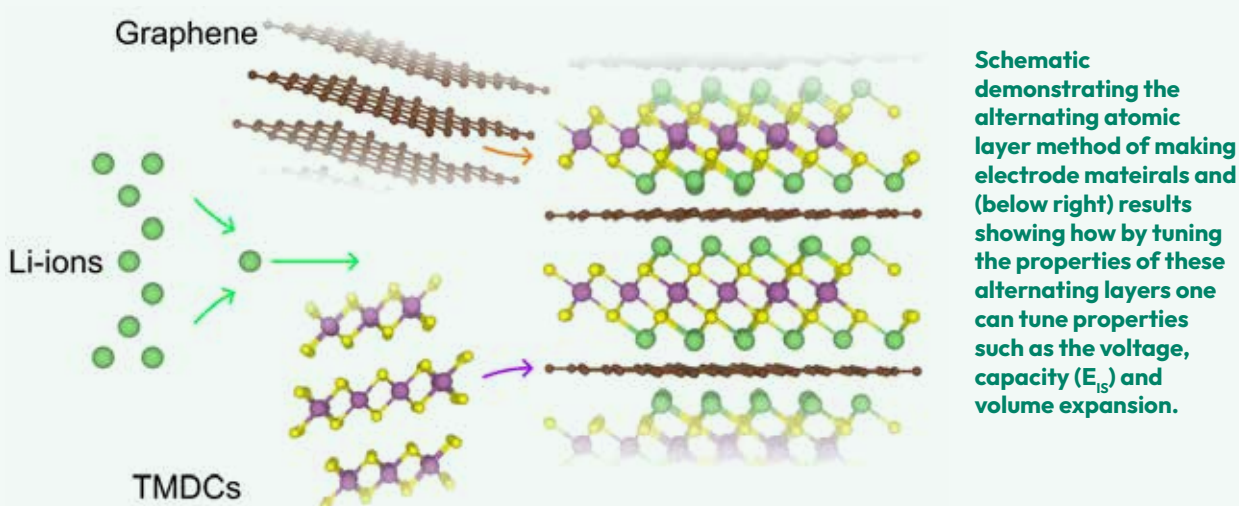
A schematic demonstrating how the overlayer is formed at the atomic level and it creates a preferable surface for photocatalytic splitting of water.

Challenges: Generally, a material that is good at absorbing sunlight may not have a good surface for carrying out the process of splitting water into oxygen and hydrogen. At Exeter, using the RAFFLE methodology, researchers have pioneered placing a thin overlayer on the surface of good absorbers of sunlight, that in turn enhance the surface reaction pathways. These surface layers also allow one to drive the carriers created by the sunlight to the surface to enhance the water splitting potential of these systems.

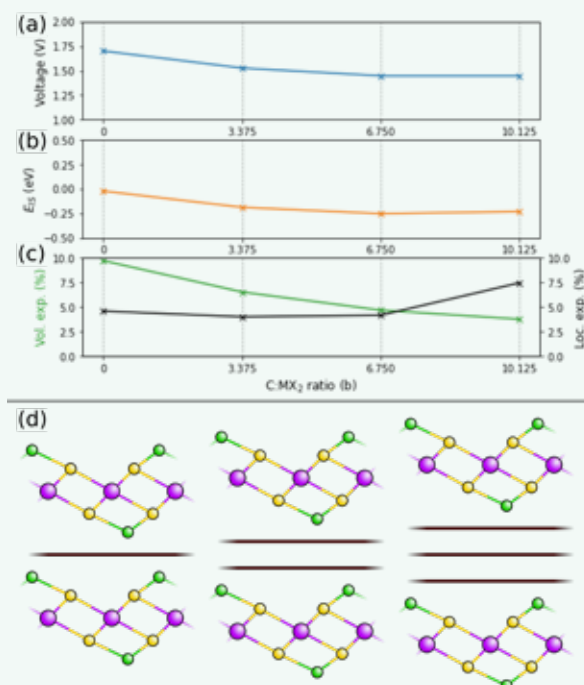
Figures reproduced from "Baker EAD, Pitfield J, Price CJ, Hepplestone SP. (2022) Computational analysis of the enhancement of photoelectrolysis using transition metal dichalcogenide heterostructures, *Journal of Physics: Condensed Matter*, volume 34, no. 37, pages 375001-375001, DOI:10.1088/1361-648x/ac7d2c." and "Taylor NT, Price CJ, Petkov A, Romanis Carr MI, Hale JC, Hepplestone SP. (2020) The Potential of Overlayers on Tin-based Perovskites for Water Splitting, *The Journal of Physical Chemistry Letters*, volume 11, no. 10, pages 4124-4130, DOI:10.1021/acs.jpclett.0c00964."

Case study: Developing novel battery electrodes using metamaterial designs

Aim: In batteries, the electrode material dictates how much power is stored and what the operating voltages are. The goal of this research was to develop new novel electrode materials which can store more energy and to provide a mechanism for changing or adjusting their voltage profile. In this project we show how making alternating layers of electrode material can achieve these goals. To do this, the chosen component materials for this are a selection of 2D materials including graphene, due to their ubiquity and cost.



Challenge: The number of potential combinations and material choices exceeds 50,000 candidates. Using advanced computational modelling, a researcher group at Exeter in conjunction with a UK battery developer have screened all of these candidates to find both general trends and show how this structuring can result in (i) improved lithium transport in the electrodes; (ii) better control of volume expansion of electrode materials during charging and discharging (iii) cost reductions with capacity enhancements of electrode materials and (iv) found new cathode material, ScS_2 , with the capacity to equal if not exceed the standard NMC cathode used in modern devices.



Figures reproduced from "Baker EAD, Price CJ, Hepplestone SP. (2024) Computational Study of the Enhancement of Graphene Electrodes for Use in Li-Ion Batteries via Forming Superlattices with Transition Metal Dichalcogenides, The Journal of Physical Chemistry C, volume 128, no. 2, pages 723-731, DOI:10.1021/acs.jpcc.3c06300."

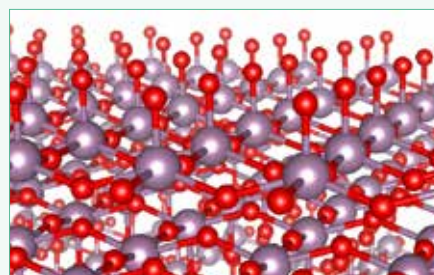
Case study: Developing novel solar cell materials

Aim: Solar cells provide a means of harnessing sunlight and converting it into electricity. This is achieved by the incident light exciting an electron-hole pair in a material. Within this material, the electron and hole should see drastically different electronic structures, such that the electron and hole are decoupled and one of the charge-carriers is able to pass into an electrode of the device.

This field is currently dominated by silicon solar cells, which is limited to a maximum theoretical efficiency of 28%. By considering other materials for solar cell devices, the hope is to reduce the production costs and offer a material with greater efficiency than that of silicon.

Challenge: Metamaterials are made to display structure on the length scales of the waves being used by the system. In solar cells, metamaterial structures can be designed to have transparent contacts such that only the main active layer is the absorber.

Solar cells need what are termed as injection layers, which are responsible for creating an effective electric field across the device. These injection layers need to (a) have an offset in their effective Fermi levels (or work functions) and (b) be optically transparent or so thin that the wavelength of the relevant light has little to no interaction i.e. a metamaterial. Researchers at Exeter have shown that careful design of these can allow a price comparable alternative to silicon solar cells which could exceed silicon efficiency.



Schematic demonstrating the atomic structure of a CaXSnYO material for use in a solar cells.

Figure reproduced from "Taylor N, Galbiati A, Saavedra M, Hepplestone S. (2020) Calcium-Stannous Oxide Solid Solutions for Solar Devices, Applied Physics Letters, volume 117, no. 15, pages 153901-153901, DOI:10.1063/5.0024947."

Hydrogen and Hydrogen storage

Research Project 1: Environmentally Friendly Synthesis of Nanoporous Materials

Short Description: Developing sustainable methods for synthesising nanoporous materials like porous polymers, carbons, and Metal-organic Frameworks (MOFs), aiming for minimal environmental impact.

Case Study: Our research explored a solid-state synthesis approach for MOFs through mechanochemical processes, significantly reducing the reliance on harmful chemicals and energy usage. This technique yielded highly efficient MOFs suitable for carbon capture and hydrogen storage, demonstrating potential for industrial scalability and enhanced environmental sustainability.

Research Project 2: Neutron Scattering Techniques for Hydrogen Research

Short Description: Utilising in situ advanced neutron scattering techniques to explore the hydrogen dynamics and interaction on a solid surface.

Case Study: Our team carried out a detailed study using in situ neutron scattering, which for the first time provided physical evidence of solid-like hydrogen confined within pores. This groundbreaking work identified optimal materials for hydrogen storage, aiding the development of safer and more efficient hydrogen energy systems.

Research Project 3: Next-Generation Hydrogen Storage Tanks via Intelligent Manufacturing

Short Description: Leveraging intelligent manufacturing to develop new-generation solid-state hydrogen storage tanks, for superior efficiency and safety.

Case Study: We engineered a breakthrough in hydrogen storage with the creation of new-generation tanks, employing intelligent manufacturing techniques for enhanced storage densities and safety measures. This scalable innovation offers a robust solution for hydrogen's safe storage and transport, marking a significant step towards its broader adoption as a sustainable energy vector. This project exemplifies the transformative potential of intelligent manufacturing in the field of energy storage.

Research Project 5: Optimisation of Hydrogen Supply Chain Management

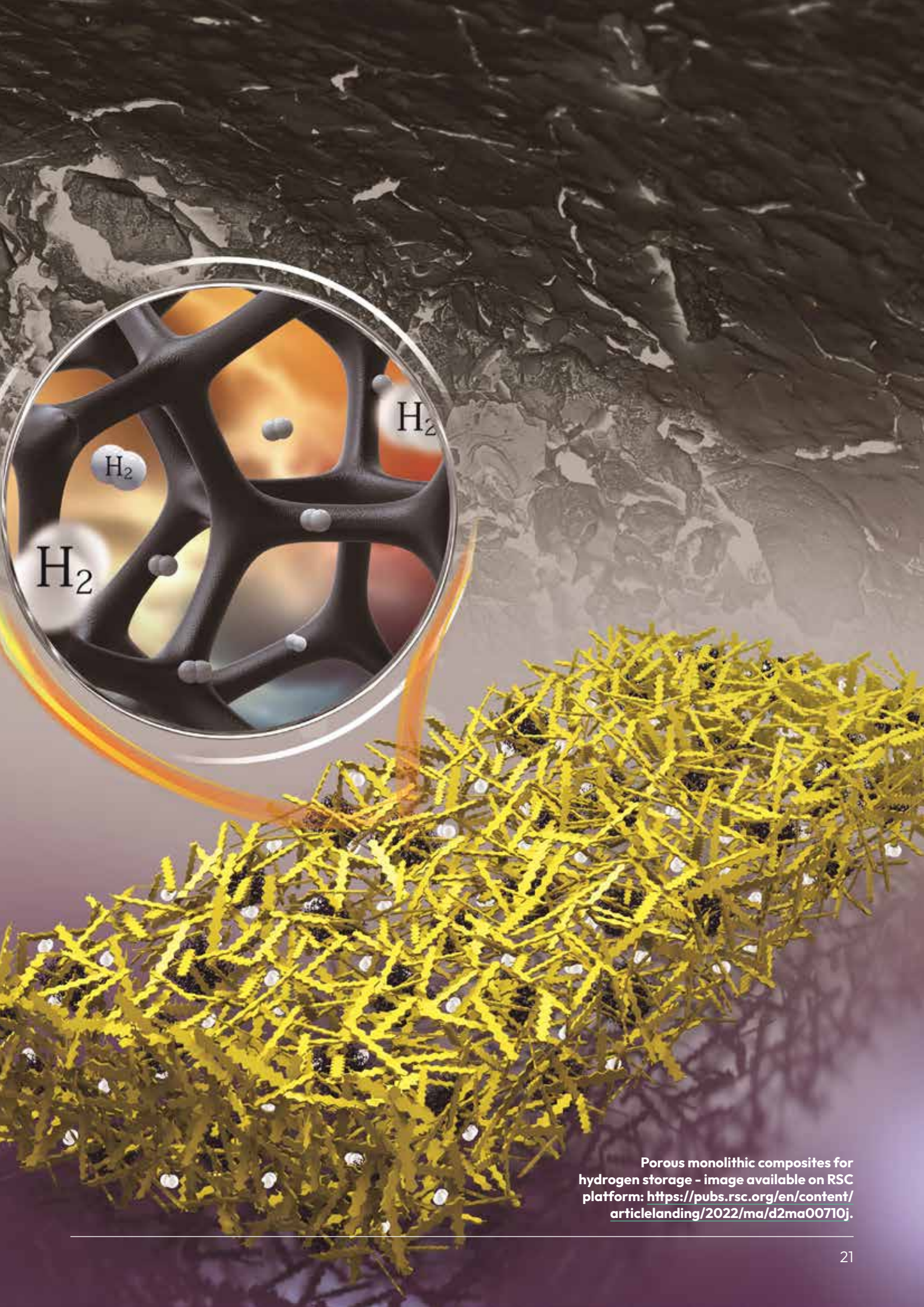
Short Description: We launched hychain.co.uk, the first market-available user-friendly web tool for designing and optimizing the hydrogen supply chain.

Case Study: Utilising hychain.co.uk, we facilitated the design and optimization of hydrogen supply chains, significantly enhancing efficiency and reducing costs. This platform has been pivotal in several case studies, proving its value in streamlining the hydrogen supply chain for various applications, thereby setting a benchmark in the industry for hydrogen management solutions.

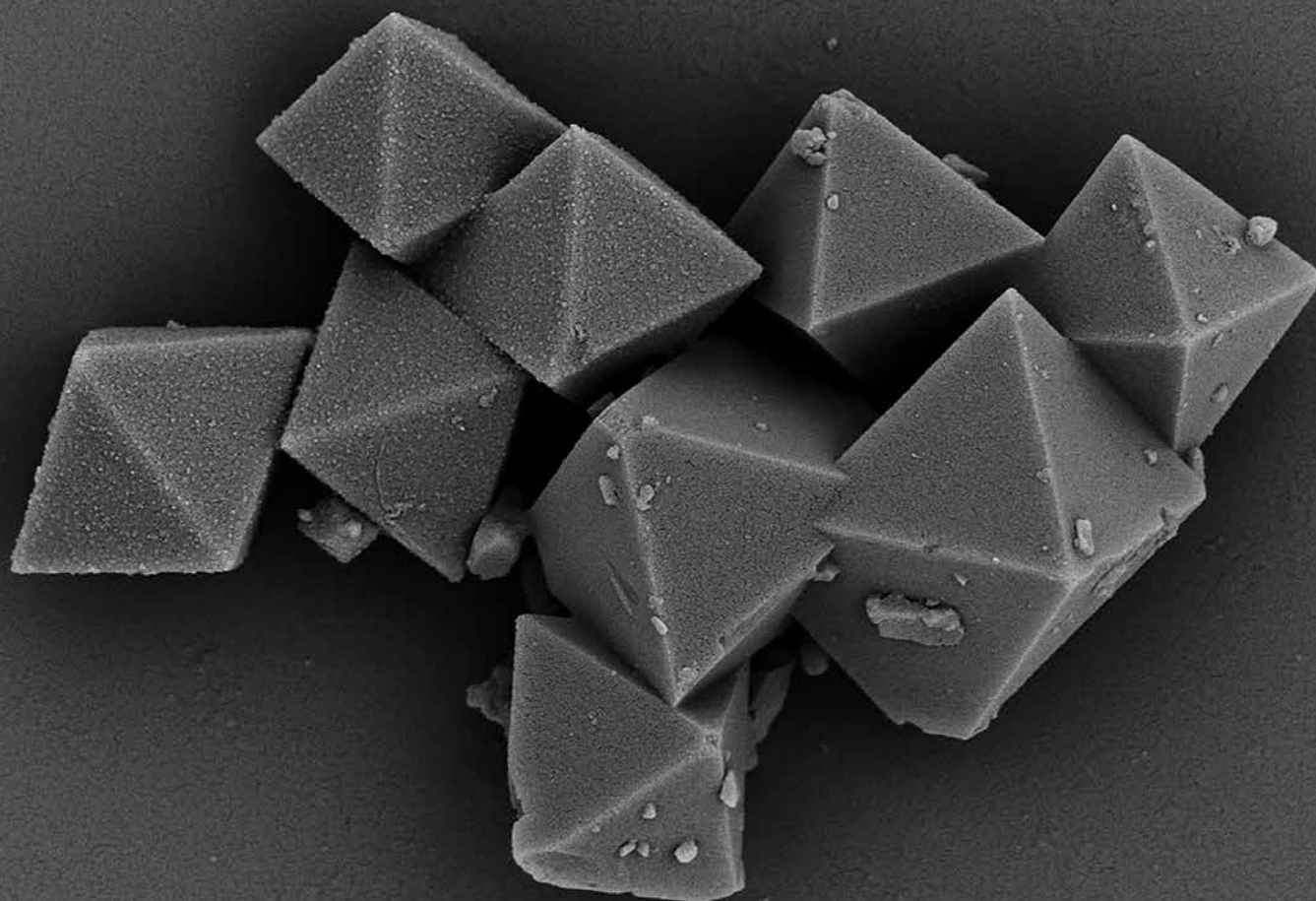
Research Project 4: Hydrogen and Deuterium Separation Processes

Short Description: Advancing separation techniques for hydrogen and deuterium to support various industrial and research applications.

Case Study: Our team developed a cutting-edge porous organic cages-based separation system that effectively separates hydrogen from deuterium. This approach presents a low-energy, cost-effective option for generating high-purity deuterium, crucial for nuclear fusion research and medical applications.

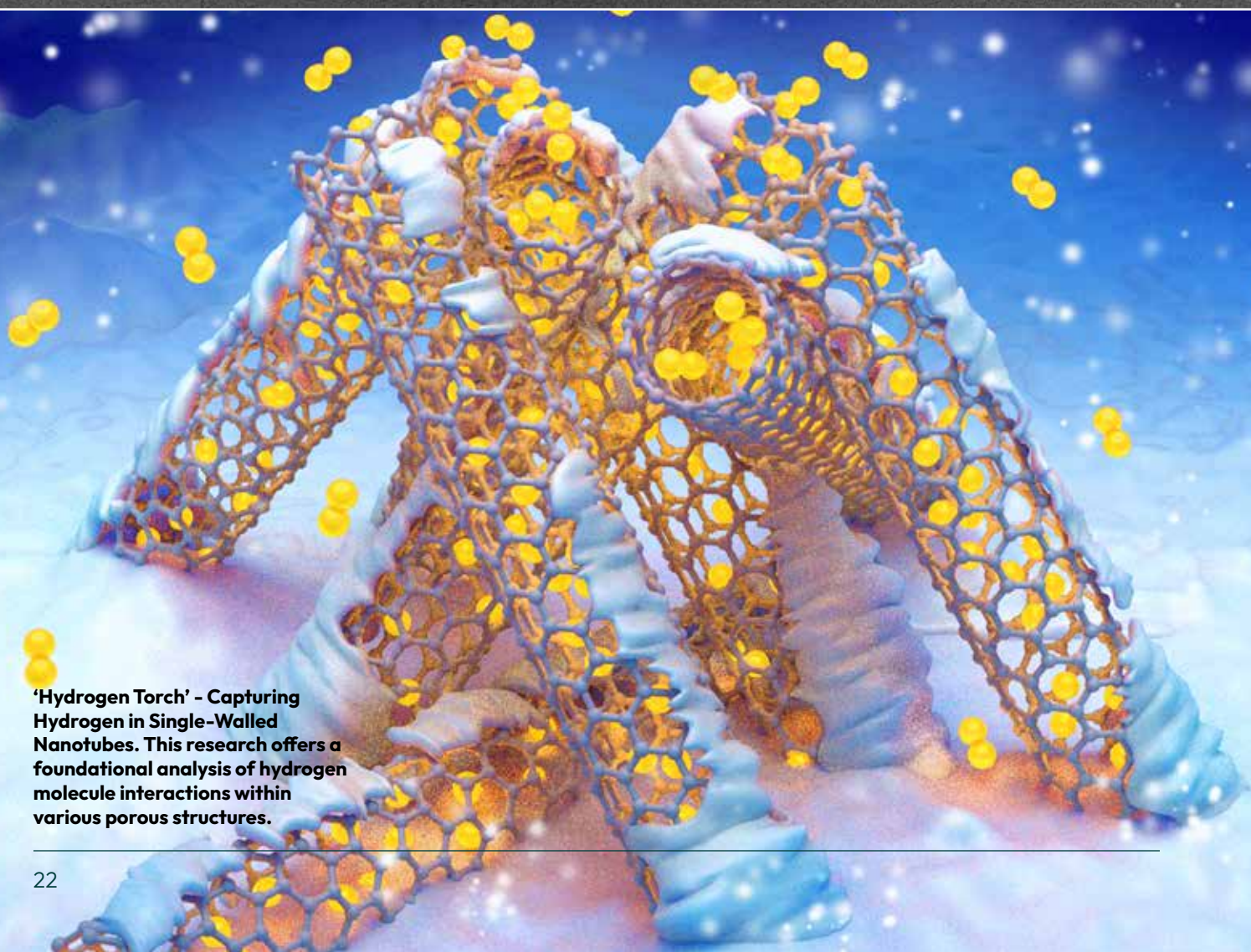


Porous monolithic composites for hydrogen storage - image available on RSC platform: <https://pubs.rsc.org/en/content/articlelanding/2022/ma/d2ma00710j>.



Microscopic View of Porous Organic Cages: Engineered for Selective Hydrogen and Deuterium Separation with Adjustable Porosity.

Figure reproduced from "Dankun Yang, Sebastien Rochat, Matthew Krzystyniak, Alexander Kulak, Jacques Olivier, Valeska P. Ting, Mi Tian (2024) Investigation of the Dynamic Behaviour of H_2 and D_2 in a Kinetic Quantum Sieving System, ACS Appl. Mater. Interfaces, 16, 10, 12467–12478, <https://doi.org/10.1021/acsami.3c17965>."



'Hydrogen Torch' - Capturing Hydrogen in Single-Walled Nanotubes. This research offers a foundational analysis of hydrogen molecule interactions within various porous structures.

Hydrogen generation from wastewater

Research within the University of Exeter focuses on the development of cost-effective novel nanostructured porous materials and relevant advanced functional nanocomposites that can achieve highly efficient hydrogen (H_2) production, hydrogen storage, carbon dioxide (CO_2) conversion, electrochemical energy storage or photocatalytic fuel generation.

Green H_2 production via photocatalytic water splitting

H_2 is widely regarded as an emission-free plausible alternative to fossil fuels to deal with the global challenges of climate change and environmental pollution. What is required for the generation of hydrogen are viable and sustainable solutions to replace current economically expensive and environmentally unsustainable methane steam reforming processes. Photocatalytic water splitting is one likely solution but requires chemically stable and highly efficient semiconductive photocatalysts to transfer solar energy to H_2 . We have developed strategies including defect engineering, doping with cationic or anionic species, and the formation of heterostructures to maximize solar light absorption in UV and visible light regions, to produce an

enhanced number of photogenerated charge carriers to the redox reaction with minimized charge recombination, and to synergistically improve the efficiency in solar-to- H_2 performance.

We have developed a series of Metal-organic frameworks (MOFs) derived photocatalytic nanocomposites with great flexibility for design and modification through various methods, including rationally modulated structures, atomically precise control of chemical compositions, optimized morphologies and precisely constructed interfaces of the (multi)metal compound heterostructures. These have proved advantageous for photocatalytic green H_2 generation and photodegradation of organic pollutants in water. Moreover, we recently also attempted to couple photocatalytic hydrogen production with photodegradation of organic pollutants or upgrading of organic pollutants into high-value-added products to realize energy conversion and pollutant removal simultaneously. This can remarkably improve the efficiency of wastewater treatment and reduced energy consumption. Exploring efficient, stable, selective, and low-cost photocatalysts for this coupled strategy is a sought-after and long-term challenge.



Enhanced H_2 production via photocatalytic water splitting on MOF-derived porous TiO_2/C nanocomposites.

Highly efficient photocatalytic H_2 evolution of $TiO_2/Cu_xO/C$ composites derived from Ti-MOF.

Figure reproduced from "Mian Zahid Hussain, Zhuxian Yang, Bart van der Linden, Werner R. Heinz, Mounib Bahri, Ovidiu Ersen, Quanli Jia, Roland A. Fischer, Yanqiu Zhu, and Yongde Xia (2022) MOF-Derived Multi-heterostructured Composites for Enhanced Photocatalytic Hydrogen Evolution: Deciphering the Roles of Different Components, *Energy & Fuels*, volume 36 (19), 12212-12225, DOI: 10.1021/acs.energyfuels.2c02319."

Publications:

3D-Printed Metal-Organic Framework-Derived Composites for Enhanced Photocatalytic Hydrogen Generation, M.Z. Hussain *et al.*, *Solar RRL*, 6 (10), 2200552 (2022).

MOFs-derived Multi-heterostructured Composites for Enhanced Photocatalytic Hydrogen Evolution: Deciphering the Roles of Different Components, M.Z Hussain *et al.*, *Energy & Fuels*, 36 (19), 12212 (2022).

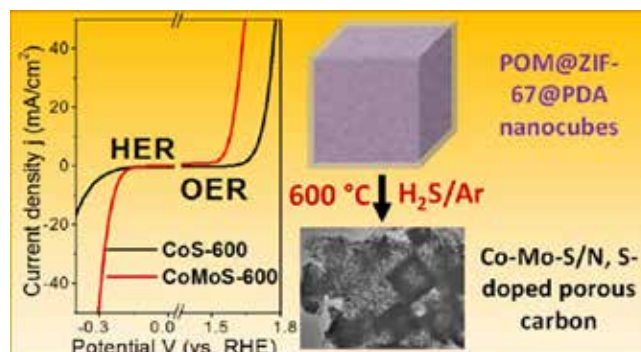
Bimetal-organic framework derived multi-heterostructured $TiO_2/Cu_xO/C$ nanocomposites with superior photocatalytic H_2 generation performance, M.Z. Hussain *et al.*, *Journal of Materials Chemistry A*, 9, 4103 (2021).

Surface functionalized N-C- TiO_2/C nanocomposites derived from metal-organic framework in water vapour for enhanced photocatalytic H_2 generation, M. Hussain *et al.*, *Journal of Energy Chemistry*, 57, 485 (2021).

Porous ZnO/Carbon nanocomposites derived from metal organic frameworks for highly efficient photocatalytic applications: A correlational study, Z. Hussain *et al.*, *Carbon*, 146, 348 (2019).

Electrochemical water splitting for green H₂ generation

Hydrogen is a zero-emission clean energy carrier that will play a crucial role in future energy scenarios and in a widely expected hydrogen economy. Massive high-purity hydrogen generation via electrochemical water splitting is a truly sustainable and effective process, although its efficiency depends on practically acceptable and efficient catalysts rather than traditional noble metal-based electrocatalysts. We have developed a series of novel carbon-based MOFs-derived transition metal compound nanocomposites and carried out systematic and in-depth investigations of these nanocomposites as low-cost, stable and highly efficient catalysts towards electrochemical water splitting for green hydrogen production. Moreover, strategies to lower the energy expenditure associated with electrochemical hydrogen production while yielding high-value products have been explored, replacing the sluggish oxygen evolution reaction with selective oxidation of alcohols. In addition, we plan to explore the presence of pollutants in wastewater (including heavy metal ions, inorganic and organic pollutants) as well as Cl⁻ in seawater to understand the effects on electrochemical hydrogen generation. It is anticipated that nanocomposite materials with excellent electrocatalytic activity and stability in water splitting for massive hydrogen production can be achieved. The delivery of such types of new electrocatalysts will mark a step-change in energy conversion technology, providing a much-needed solution.



MOF-derived Co-Mo sulfide/carbon composites as bifunctional catalysts towards electrochemical water splitting for H₂ and O₂ production.

Figure reproduced from “Huang, Zheng and Yang, Zhuxian and Jia, Quanli and Wang, Nannan and Zhu, Yanqiu and Xia, Yongde (2022) Bimetallic Co-Mo sulfide/carbon composites derived from polyoxometalate encapsulated polydopamine-decorated ZIF nanocubes for efficient hydrogen and oxygen evolution, *Nanoscale*, The Royal Society of Chemistry, volume 14, (12), 4726-4739, 10.1039/D1NR07913A.”

Greenhouse gas CO₂ capture and chemical conversion

Highly porous materials with tunable functionalities can efficiently and selectively adsorb/capture CO₂ gas as well as simultaneously convert CO₂ to value-added chemicals (such as dimethyl carbonate) or materials. We have deployed different strategies, including catalytically chemical conversion, electrochemical CO₂ reduction and photocatalytic CO₂ reduction to convert the adsorbed CO₂ to valuable compounds. We are demonstrating that earth abundant transition metal-based functional materials can effectively transform greenhouse gas CO₂ to valuable chemicals.

Publications:

- Bimetallic Co-Mo sulfide/carbon composites derived from polyoxometalate encapsulated polydopamine-decorated ZIF nanocubes for efficient hydrogen and oxygen evolution, Z. Huang *et al.*, *Nanoscale*, 14, 4726, (2022).
- Bimetallic Fe-Mo sulfide/carbon nanocomposites derived from phosphomolybdic acid encapsulated MOF for efficient hydrogen generation, Z. Huang *et al.*, *Journal of Materials Science & Technology*, 2021, 84, 76, (2021).
- Polyoxometallates zeolitic-imidazolate-framework derived bimetallic tungsten-cobalt sulfide/porous carbon nanocomposites as efficient bifunctional electrocatalysts for hydrogen and oxygen evolution, Z. Huang *et al.*, *Electrochimica Acta*, 330, 135335 (2020).
- Improved hydrogen release from ammonia borane confined in microporous carbon with narrow pore size distribution, Z. Yang *et al.*, *Journal of Materials Chemistry A*, 5, 15395 (2017).
- Tungsten disulphide nanorattle: A new type of high performance electrocatalyst for hydrogen evolution reaction, Y. Wen *et al.*, *J. Power Sources*, 307, 593 (2016).
- Enhanced catalytic activity of H₂ heat-treated porous ceria for direct conversion of carbon dioxide into dimethyl carbonate, Z. Yang *et al.*, *Chemical Engineering Journal*, 486, 150339 (2024).
- Cu-Based Catalytic Materials for Electrochemical Carbon Dioxide Reduction: Recent Advances and Perspectives, L. Ma *et al.*, *Advanced Energy and Sustainability Research*, 4, 2300034 (2023).
- Surface Structure Engineering of PdAg Alloys with Boosted CO₂ Electrochemical Reduction Performance, Xianghua Yang *et al.*, *Nanomaterials*, 12 (21), 3860 (2022).
- Atomically homogeneous dispersed ZnO/N-doped nanoporous carbon composites with enhanced CO₂ uptake capacities and high efficient organic pollutants removal from water, B. Chen *et al.*, *Carbon*, 95, 113-124 (2015).
- Preparation and carbon dioxide uptake capacity of N-doped porous carbon materials derived from direct carbonization of zeolitic imidazolate framework, F. Bai *et al.*, *Carbon*, 79, 213-226 (2014).
- Superior CO₂ Adsorption Capacity on N-doped, High-Surface-Area, Microporous Carbons Templated from Zeolite, Y. Xia *et al.*, *Advanced Energy Materials*, 1 (4), 678-683 (2011).

Materials and Technologies for the Built Environment

The implementation of advanced materials in the civil engineering industry is significantly enhancing the energy performance and environmental efficiency of buildings. Emphasis in optimising Smart Buildings for future climates is critical. Our research within the University of Exeter is developing techniques that are leading to effecting changes in the whole construction process, from design to implementation.

More of 50% of the world's population lives in cities, making the built environment responsible for the emission of more than 14 gigatonnes of carbon dioxide equivalent every year. Our research delivers solutions to reduce the environmental impact of the built environment and to improve its liveability.

SHUTTERING project

Funded by EPSRC and developed in collaboration with the University of Cambridge, SHUTTERING addresses the critical limitations of formwork and concrete in current methods of construction. The project investigates the application of auxetic elements as formwork and reinforcement alongside low-carbon concrete based on alkali-activated binders. The project outcomes will improve material efficiency, reduce waste, promote circular economy, and pave the way for novel, creative designs of optimised structural elements. Other applications of the materials developed in this project can be predicted in structural retrofitting with auxetic materials, and in new approaches for aesthetic finishing of concrete elements, such as colour, texture, and engraved graphics.

Auxetic meshes are embedded in concrete to understand their contribution in terms of deformation control, energy dissipation, and intrinsic confinement. The project also investigates the feasibility of complex double curvature shapes thanks to the synclastic nature of the meshes, and explores new shapes, texture, and appearance of translucent concrete.

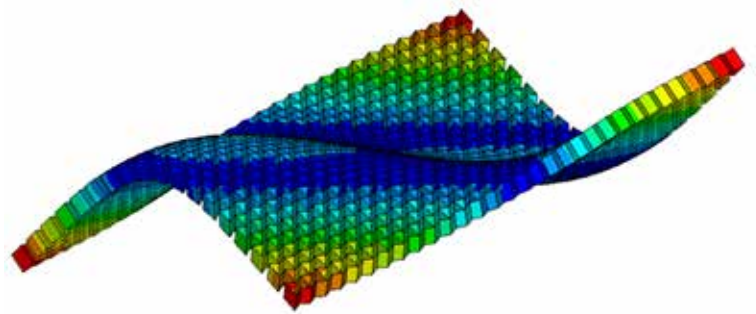
Translucent nature of plastic auxetic meshes.



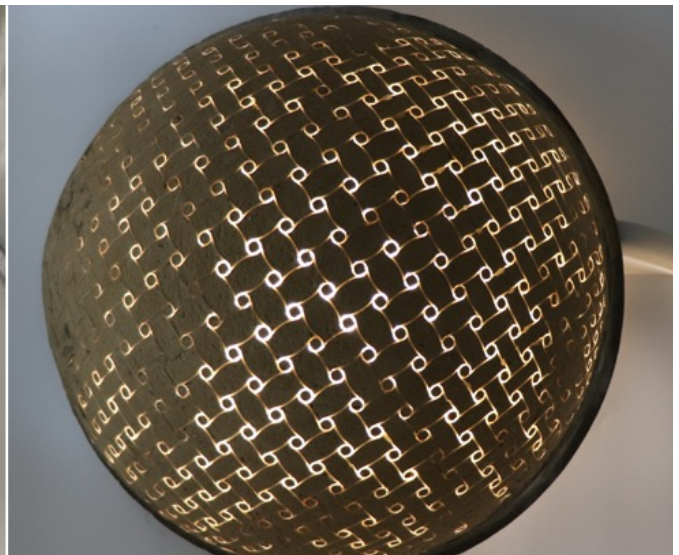
Concrete panels with embedded auxetic meshes to investigate the behaviour of the structural element.

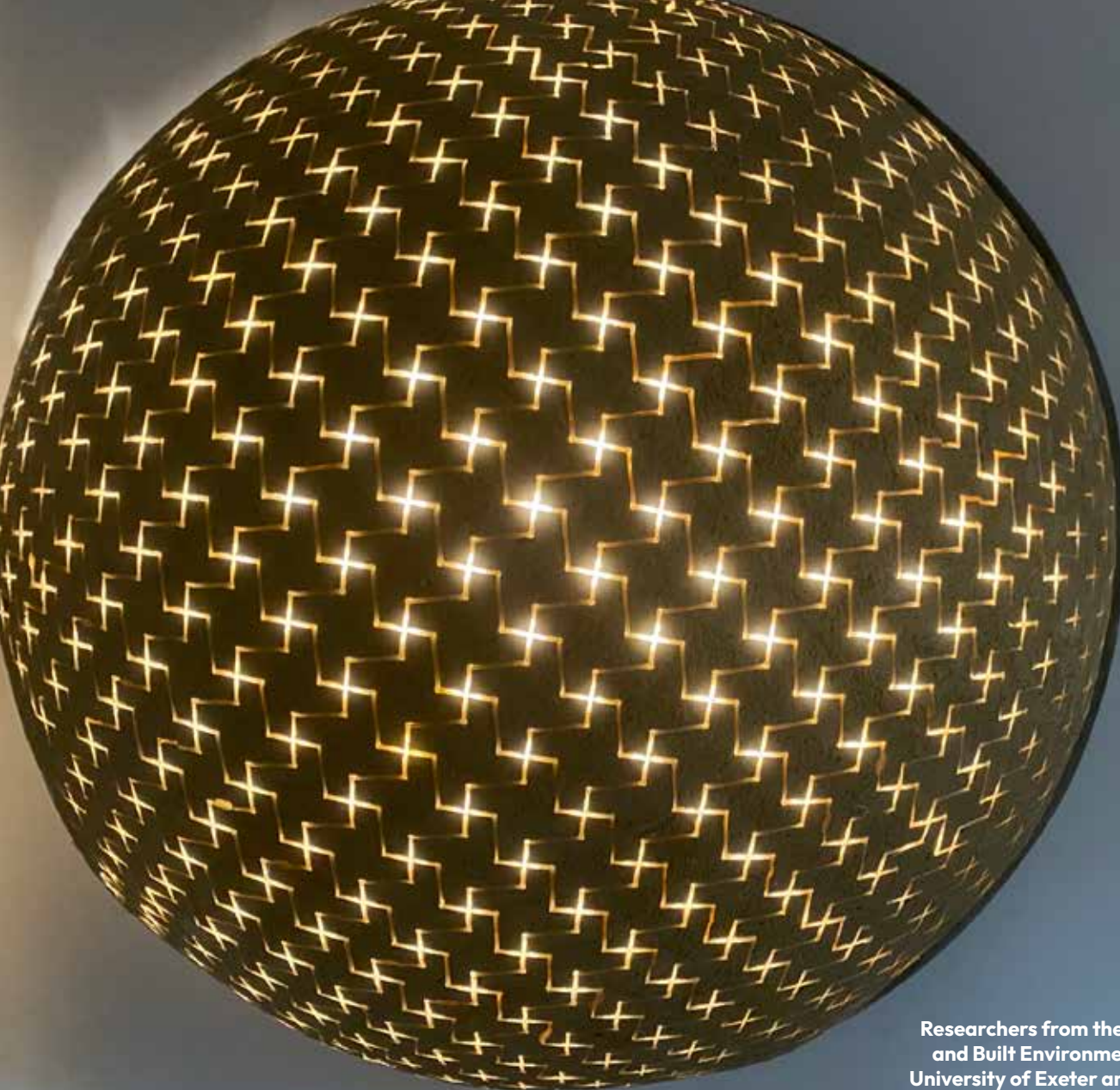


Figures included in a submitted extended abstract: Hajasadeghi M., Momoh E., Jayasinghe A., Vinai R., Kripakaran P., Evans K., Orr J. COMPRESSION PERFORMANCE OF CEMENTITIOUS MATERIAL-FILLED AUXETIC PANEL COMPOSITE STRUCTURES, 78th RILEM Annual Week & RILEM Conference on Sustainable Materials & Structures: Meeting the major challenges of the 21st century - SMS 2024, conference, Toulouse 25 to 30 August 2024.



Numerical model showing the potential of Auxetic Mesh being engineered into complex shapes with double curvature.

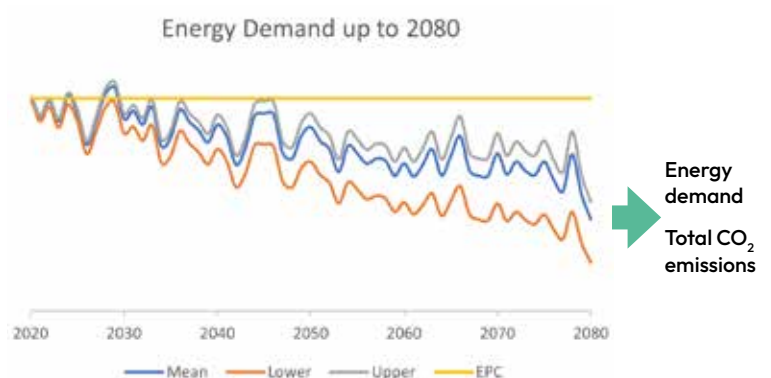




Researchers from the Infrastructure and Built Environment group at the University of Exeter are investigating novel and exciting concrete systems for a sustainable and visionary construction industry.

Long term building performance

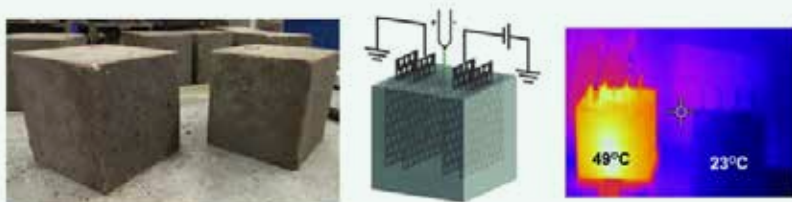
Buildings are long term assets which must work in the current climate and in the future. Using detailed probabilistic future climate scenarios, building information, building utilisation patterns and building performance simulation we can predict how the building will behave over the next 75 years. In this way we can not only reduce the embodied carbon of the building by optimising its design and use of materials, but also minimise the whole life carbon taking into account the impact on heating, ventilation and cooling energy, as well their related carbon emissions as the climate warms.



Case study: Engineering concrete at the nanoscale

Our work aims to decarbonise cement and concrete using graphene nanomaterials.

“Concrete is tipping us into climate catastrophe.” reads the headline title of The Guardian article by J. Vidal (25 Feb 2019) who states that “Nearly 6% of all UK greenhouse gas emissions, and up to 8% of the world’s, are now sourced from cement production.” For every tonne of traditional cement produced, 1.25 tonnes of CO₂ is released into the atmosphere. With the rising threat of climate change and greenhouse gasses it is becoming more important than ever to reduce the carbon footprint of the construction industry. In addition, the urbanization of areas subject to major environmental risks, e.g. flooding and earthquakes, poses strict demands on resilient construction materials which should ideally be easily accessible. This makes it difficult if not impossible for concrete to be replaced in construction by less CO₂ heavy materials such as timber as they pose longevity and resilience problems. It is evident that concrete will continue to be an important aspect of construction and the UK economy, so the key is to reduce the environmental impact of concrete as a material. The addition of graphene to concrete does just that as demonstrated by the group at Exeter in 2018 followed by timely patents. Tests have shown that the addition of graphene cuts down the CO₂ emissions of traditional concrete by 50% bringing it to approximately 446kg/tonne without sacrificing the strength or lifetime of the material. For this reason, Concrene™ our patented formulation of graphene reinforced concrete is rapidly entering in the manufacturing lines or R&D lines of major concrete market holders and stakeholders around the world have quickly adopted graphene-enhanced concrete. For example, Fairview Hearthside in the US has commercialised the world’s first graphene enhanced concrete product embedding Concrene™. Graphene-enhanced concrete also offer other advantages over conventional concrete for heating applications. The addition of graphene improves the electrical and thermal conductivity of the concrete. This conductivity enables the concrete to be used in applications where heating elements are embedded within the material, such as in floor heating systems or de-icing applications for roads and pavements. Graphene-enhanced concrete can provide more efficient and uniform heating compared to conventional concrete, as it can distribute heat more evenly throughout the structure.



Graphene-enhanced concrete blocks utilized for multifunctional applications, showcasing improved strength, electrical conductivity, and thermal properties. Notably, graphene-enhanced concrete exhibits prolonged heat retention compared to conventional concrete.

Figure reproduced from "D. Dimov, I. Amit, O. Gorrie, M. D. Barnes, N. J. Townsend, A. I. S. Neves, F. Withers, S. Russo, M. F. Craciun, Ultrahigh Performance Nanoengineered Graphene-Concrete Composites for Multifunctional Applications, *Adv. Funct. Mater.* 2018, 28, 1705183. <https://doi.org/10.1002/adfm.201705183>."

Concrete 3D printing utilising secondary resources

The Problem: Concrete 3D printing is an emerging technology that allows for on-demand construction of buildings and infrastructure using concrete as the primary printing material. While offering many potential benefits such as customisation, speed of construction, and design flexibility, a major limitation of current concrete 3D printing methods is the high carbon footprint associated with concrete production from primary resources like cement. On the other hand, geomaterial waste represents half of the waste volume generated in EU-27. These waste geomaterials generally exhibit poor engineering characteristics that prevent their direct reuse on construction/mining sites. However, if adequately treated, they could represent an excellent resource for construction purposes with significant money saving and reduction in the environmental footprint, thus contributing to the establishment of a circular economy.



Laboratory Scale Concrete 3D Printer Developed by Our Team.

Our Solution: We are developing strategies and tools for sustainable repurposing of waste geomaterials originating from geoengineering activities within the realm of concrete 3D printing technology. Our primary goal is to ascertain methods for transforming these waste geomaterials into high-value, durable materials that not only meet stringent engineering standards but also generate a positive revenue stream. We are actively engaged in developing comprehensive protocols, models, and specialised tools. These innovations are designed not only to enhance the engineering properties of waste geomaterials but also to ensure a consistent level of performance throughout the service life of 3D-printed elements and structures constructed from these materials. Our approach takes into consideration the unique conditions of each site, thus guaranteeing optimal performance tailored to site-specific nuances. This commitment to improving waste geomaterials for 3D printing applications underscores our contribution to sustainable practices in the field, simultaneously addressing environmental concerns and paving the way for innovative and economically viable solutions.

Publications:

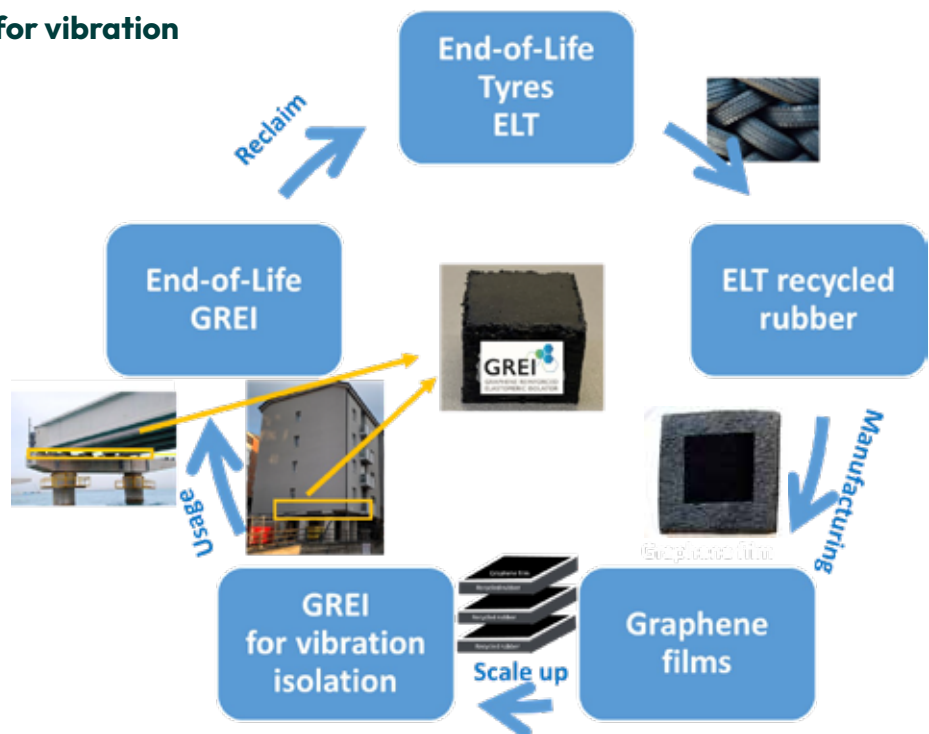
Ultrahigh performance nanoengineered graphene–concrete composites for multifunctional applications, D. Dimov *et al.*, *Advanced functional materials* 28 (23), 1705183 (2018).

A sustainable metamaterial for vibration mitigation

GREI - Graphene Reinforced Elastomeric Isolators

GREI combines end-of-life tyre recycled rubber and graphene to create a sustainable functional material for vibration isolation.

GREI is suitable for bridge bearings, seismic bearings for buildings, but also for vibration isolation of sensitive equipment in medical and aerospace environment.



Biobased building materials – MISCRETE project

The team have developed a sustainable lightweight construction block using lime-based binders and miscanthus fibres, named Miscrete.

Miscanthus is a perennial, fast growing, and high-yield giant grass that can be produced on agricultural land as well as on marginal soils, with no irrigation nor major phosphate/fertiliser demand. It is well understood and established in UK agriculture as a biomass material.

The research carried out at the University of Exeter combines the potential of lightweight, low thermal conductivity materials with the high carbon sequestration features of miscanthus fibres, delivering a sustainable, carbon negative construction material with several benefits. The low density (of about 350 kg/m³) and the low thermal conductivity ($\lambda \approx 0.15$ W/mK) are key properties for the use of Miscrete in a range of building elements (blocks and panels) that, thanks to the CO₂ sequestered during the growth of the crop, and the re-carbonation of lime-based binder, have negative

embodied carbon (about -130 kg CO_{2,eq}/m³).

The research successfully demonstrated the production of more than 300 miscrete blocks using traditional concrete block equipment, as well as the realisation of a prototype of composite panel with waste-derived alkali-activated concrete with brick wall texture for retrofitting purposes.

The University is seeking partners for the scale up of the technology.

A lightweight building material¹...
 ... made with renewable components²...
 ... with self-weight bearing capacity³ ...
 ... produced with standard block technology⁴...
 ... with improved insulation properties⁵ ...
 ... and negative carbon emissions⁶ !

¹ Bulk density < 350 kg/m³; ² Miscanthus is a perennial grass with yearly yield of 10t/ha; ³ Load tests demonstrated that blocks could bear a load between 260 and 337 times their own weight; ⁴ > 200 blocks were produced with a semi-automatic vibro-press designed for standard concrete applications; ⁵ Thermal conductivity values were measured in the range of 0.10 to 0.15 W/mK; ⁶ CO₂ emissions in the range of -130 kg CO_{2,eq}/m³, each block able to sequester about 0.8 to 0.9 kg CO_{2,eq}, representing more than 10 kg of CO₂ sequestered per each m² of miscrete block wall.



Miscrete lightweight construction blocks.



Outer layer: recycled brick powder for alkali activated concrete (<70% CO₂ emission compared to traditional concrete).

Insulation layer: Miscrete material.

Inner layer: structural system for panel installation.

Low carbon binders

Novel cementitious systems for the partial or total substitution of Portland cement in concrete have been investigated, assessing the potential of waste streams to be recycled as components of low carbon binders. Extensive research on the use of

aluminosilicate-rich materials for the production of alkali activated binders has been successfully carried out, and calcium-based industrial waste has also been trialled for the development of lime-based binders.



Biobinders: Eco-Friendly Approach for Soil Stabilisation

The Problem: Conventional soil improvement techniques, like Ordinary Portland Cement (OPC), have historically contributed significantly to greenhouse gas emissions. The CO₂ emission related to cement used in soil improvement is about 2% of the total CO₂ emission by cement. Replacing 10% of cement usage with low-carbon materials in geotechnical engineering applications could lead to an annual reduction of 6.1 million tonnes of CO₂ worldwide.

Our Solution: Bio-cementation emerges as a promising avenue to curtail carbon emissions, potentially reducing them by up to 70% in soil improvement processes. Our research endeavours focus on the development of biobinders,

encompassing biopolymers, fungi, Microbial-induced Carbonate Precipitation (MICP), and Enzyme-induced Carbonate Precipitation (EICP). These biobinders offer environmentally friendly solutions for diverse applications, ranging from soil improvement and enhanced soil erosion resistance to the stabilisation/solidification of contaminated soils and mine tailings in both geotechnical and mining engineering.

Beyond soil enhancement, our research extends to leveraging biological methodologies to boost plant productivity, enhance soil fertility, valorise construction waste materials, treat wastewater, and innovate in self-healing concrete and clay 3D printing technologies.

Application of biopolymers in sandy soil stabilisation.



Additive Layer Manufacturing, Polymers and Composites

The Exeter Technologies Group combines materials science in polymers and composites, with manufacturing techniques and modelling expertise. It aims to support the development of materials, products and processes whilst developing new fundamental knowledge about the material and process interactions.

Exeter Technologies Group (ETG) – Materials and Manufacturing

Find more about ETG:



The Exeter Technologies Group combines materials science in polymers and composites, with manufacturing techniques and modelling expertise. It aims to support the development of materials, products and processes whilst developing new fundamental knowledge about the material and process interactions. It works across three centres (X-AT, CALM and CALMARE) with its research covering aspects such as material characterisation, additive manufacturing, circular economy and the development of sustainable materials and processes:

- **X-AT** - Established in 1997 as the Polymer Centre of the South West, X-AT works with industry partners to develop new polymer and composite solutions, investigating the interaction between materials and manufacturing processes.
- **CALM (Centre for Additive Layer Manufacturing)** – Recognised as a leading centre of excellence for Additive Manufacturing with High Performance Polymers, CALM has unique capabilities and knowledge with regards to the development of AM materials and processes for high temperatures and performance.
- **CALMARE** (Centre for Alternative Materials and Remanufacturing) – For over a decade, CALMARE has been carrying out research into the more sustainable use of polymers and composites, investigating concepts such as the circular economy, biomaterials, recycling and remanufacturing.

Facilities

ETG has extensive material characterisation, manufacturing and testing facilities all housed within the same research group. It's modern rheology and thermal characterisation suite (e.g. DSC, TGA, DMA, Flash DSC etc) includes all the tools it needs to provide in-depth analysis of the materials looking at aspects such as crystallisation kinetics to optimise production processes. It's powder analysis equipment and in-house modelling

techniques allow large numbers of powders to be analysed quickly and cost effectively with accurate predictions of how they will behave in the Additive Manufacturing (AM) technique of Powder Bed Fusion (PBF). The AM group focuses on the use of high temperature polymers such as Polyaryletherketones (PAEKs) and is recognised as a leading research centre in this area with an impressive array of equipment. These include the high temperature PBF systems (EOS P 800 and P 810) its Kuka robot for large format printing and 5 separate Material Extrusion systems including Minifactory, Intamsys and 3D Gence. All of this sits alongside traditional manufacturing such as injection moulding and compression moulding, and an array of mechanical and electrical test equipment.

Victrex Partnership

The jointly funded Victrex partnership is an example of how ETG provides strategic industrially focused research. Victrex is one of the global leaders in Polyaryletherketone (PAEK) polymer materials and manufacturing. The success of the initial 5-year partnership (2018-23) between ETG and Victrex means this has now been renewed for another 5 years. Whilst the initial work focused on AM, the new partnership will continue the journey of discovery with a focus on clarifying the underpinning science across a multitude of PAEK-related processes including and beyond Additive Manufacturing (AM). It will utilise and develop knowledge crossing into sustainability, predictive modelling and simulations.

The collaboration has produced a range of industrial and scientific outcomes from the development of new PAEK materials tailored for AM, to patents, new collaboration projects, scientific publications, case studies and unique insights into the fundamental science of PAEK materials and AM.

The high impact potential of the work and strategic alignment of both organisations is driving this new partnership, with the project aims focused on the Digital 4.0 transformation strategy. The outputs

will accelerate innovation and delivery to end-users through virtual experimentation, reduced time for polymer design and creation of tailored PAEK polymer solutions.

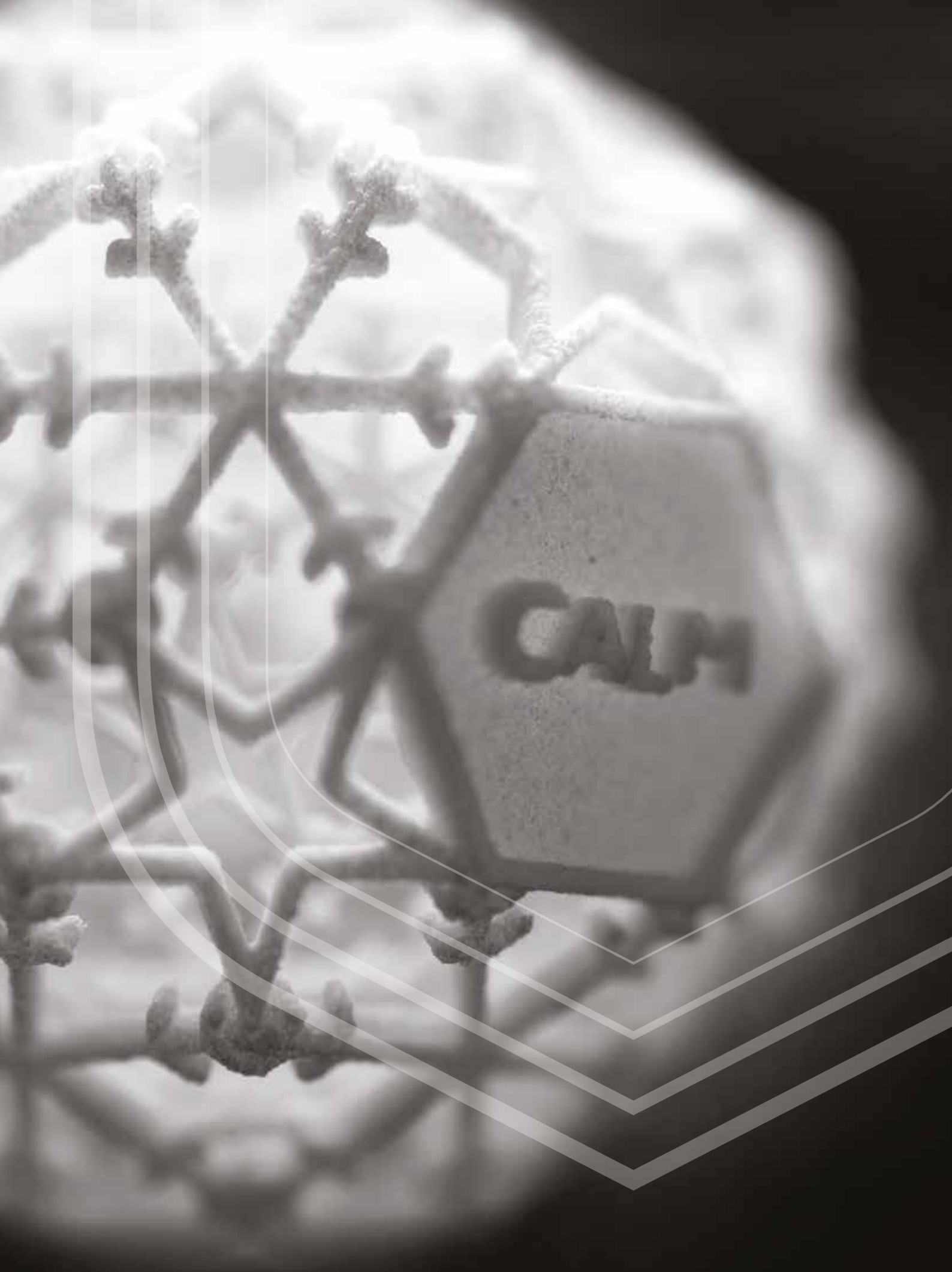
Project Examples - Additive Manufacturing

Large format printing, overprinting and nano-composite development

ETG has had a lot of success in recent years acquiring Innovate UK funding. Work with multiple partners and end-users has explored large format printing with high performance polymers. The end solution offered a hybrid technology combining overprinting with material extrusion onto composite forms. Results exceeded expectations giving even better bonding than overmoulding, with temperature being the critical factor. This project followed on from an earlier study that looked at novel techniques for combining nano-particles with PAEK polymers to develop new bespoke lightweight multifunctional materials that can be 3D printed using powder bed fusion technology and material extrusion, offering benefits in terms of mechanical performance and electrical conductivity. Novel methodologies for combining materials in the optimum form for Additive Manufacturing were developed and the team are working with the industrial partners to further investigate these options for commercialisation.

Project Examples - The circular economy

ETG is working closely with a variety of companies, researching the challenges with implementing new sustainable and circular solutions, developing the technologies necessary to facilitate this change. Its research spans a wide variety of materials, processes and products from looking at wetsuit recycling with Finisterre and new sustainable birth pool liners (Edel Immersys), to implementing new in-line monitoring techniques for recycling companies (Berry – BPI and Fiberight) and novel composite solutions (Recorlite™) for automotive applications (Foresight Innovations).



Research projects

EPSRC EP/N034627/1 – Novel high performance polymeric composite materials for additive manufacturing of multifunctional components

The aim of the project was to develop novel high performance, nanocomposite feedstock powder materials and filament for two processes: Laser Sintering and Fused Deposition Modelling (FDM). It examined the potential use of inorganic fullerene-like tungsten disulfide (WS₂) as nanofillers for high value, PAEK (Poly Aryl Ether Ketone) based products.

The incorporation of these nanomaterials has been shown to improve thermal, mechanical and tribological properties of various thermoplastic polymers. It reduces wear and the coefficient of friction as well as offering processability benefits with dispersion characteristics that are superior to 1D and 2D nanoparticles. They are also the best shock absorbing cage structures known to mankind and importantly, they are non-toxic, and thermally stable.

The team has carried out extensive research on WS₂ inorganic fullerenes and their applications in nanocomposites using conventional fabrication techniques and has recently invented a new rotary manufacturing technology for the continuous production of WS₂ inorganic fullerenes.

EPSRC EP/L017318/1 – Particle shape and flow behaviour in Laser Sintering: from modelling to experimental validation

This project investigated the way the polymeric powders of different shapes and sizes flow, interact and sinter in the laser sintering process, through modelling and experimental validation. The spreading and compaction of the powder is an important part of the LS process. A non-uniform layer of powder leads to high porosity and weaker bonding between layers and therefore a structure with poor mechanical performance. Similarly, the size and shape of particles can change the sintering process.



Topologically optimised demonstrator bracket made of experimental Victrex PAEK material. Design owned by 3T RPD Ltd., who reserves all rights to it.

Larger contact areas between particles lead to a good sintering profile and ultimately to a high-density part and good mechanical properties. Surface area of particles, polymer viscosity and surface tension were characteristics which were investigated when modelling the flow and sintering process. It was a highly innovative project, and its findings have the potential to help unlock the materials limitations for polymeric laser sintering. This allows rapid expansion into a wider range of higher value applications due to lower powders costs, wider choices and better understanding of their behaviour within the manufacturing process.



Poly Ether Ether Ketone (PEEK) polymers for high temperature laser sintering (HTLS)

With the limited range of materials available for HTLS, this jointly funded PhD focused on the investigation of a new medical grade of PEEK. The study examined some of the key requirements needed for the successful development of new materials in LS processes at experimental and theoretical levels. This was the first study on a medical PEEK grade on a powder bed system. Two medical grades of PEEK, 150PF and 450PF (OPTIMA LT3 and LT1), have been quantitatively investigated in parallel with well-established LS polymers in terms of particle size particle morphology and flow behaviour. A calculation of the inter-particle interactions has been evaluated for all the materials proposed. These analyses, coupled with two strategies for the improvement of powder flowability, have formed a systematic and fundamental approach for studying powders in LS.

PEEK OPTIMA® LT1 grade was selected for optimisation into the HTLS system, EOSINT P 800. The HTLS processing parameters and their effect on the mechanical characteristics of the laser sintered units were investigated and optimised. New insights into the HTLS mechanisms and functionalities of the EOSINT P 800 system were provided. The investigation also resulted in the proposal of a technique for the prediction of one of the HTLS processing temperatures from the powder properties as well as assessing a formula for linking material properties to processing parameters. Lastly, two case studies were performed with two long term medical implants manufactured utilising PEEK OPTIMA® LT1, and then tested.

Additional related research projects

- CDE 31809 – Development of CNT/PEEK structures using AM, for lightweight, high performance and multifunctional applications.
- UTOPIUM – Ultimate Toughness and Other Properties by Ultimate Materials
- CDE 36453 – High temperature additive manufacturing for rapid manufacture and adaption of bespoke military equipment
- CDE100404 – High temperature additive manufacturing with embedded fibre optic sensors
- DSTL/AGR/00249/01 – Cost-benefit analysis (to the supply chain) of additive manufacturing
- EPSRC EP/M01777X/1 – Re-Distributed Manufacturing and the Resilient, Sustainable City (ReDReSC)

Publications:

[Powder Bed Fusion Versus Material Extrusion: A Comparative Case Study on Polyether-Ether-Ketone Cranial Implants, Y. Liu *et al.*, 3D Printing and Additive Manufacturing, 10, 5 \(2022\).](#)

[Multiscale Porous Poly \(Ether-Ether-Ketone\) Structures Manufactured by Powder Bed Fusion Process, Liu Y *et al.*, 3D Printing and Additive Manufacturing, 11, 1 \(2022\)](#)

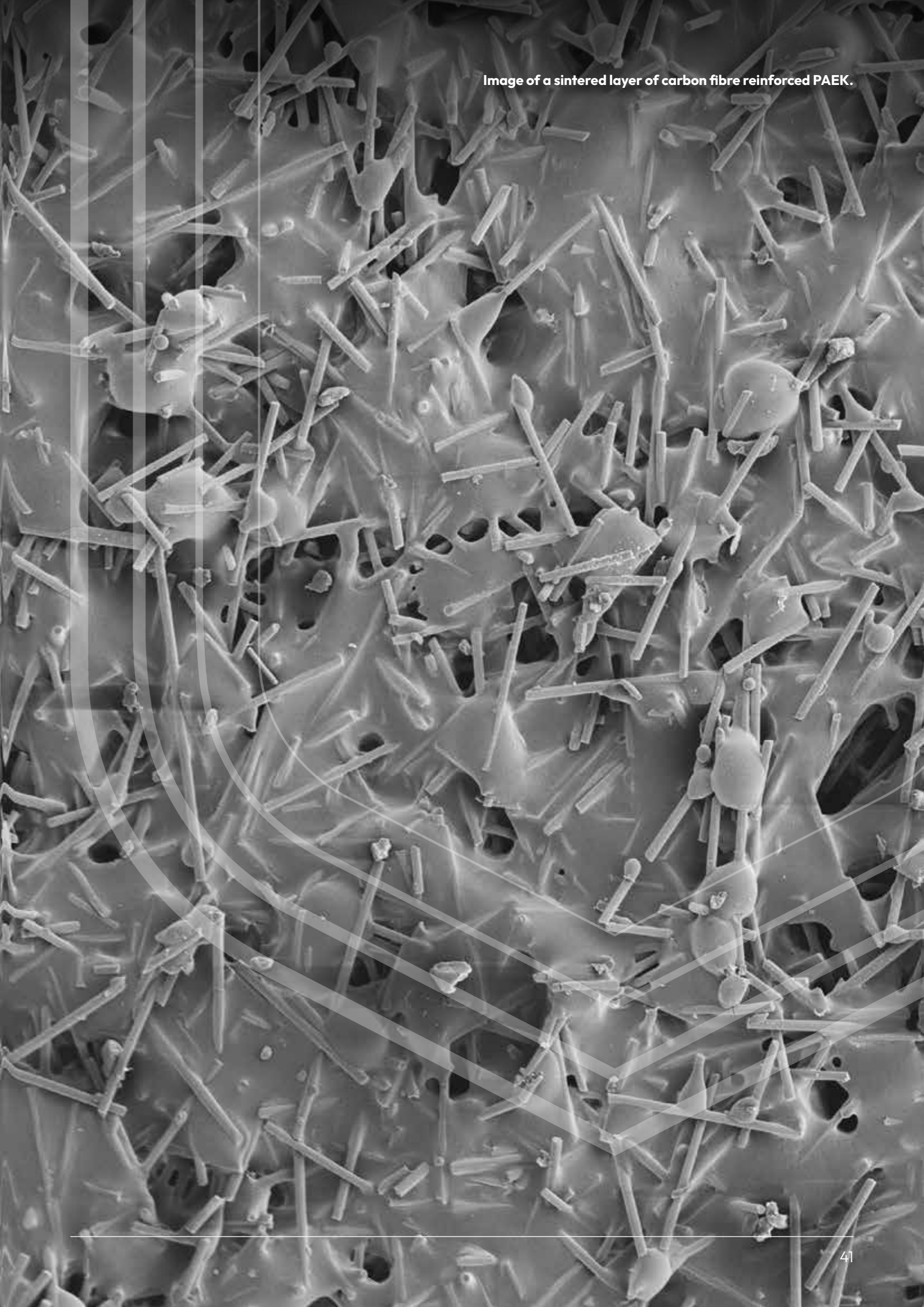
[PEEK filament characteristics before and after extrusion within fused filament fabrication process, CA Comelli *et al.*, Journal of Materials Science, 57, 1, 766, \(2022\)](#)

[Special issue: PAEKing ahead into the 21st century, S. Lowe *et al.*, POLYMER INTERNATIONAL, 70, 8, 997 \(2021\).](#)

[Mechanical property variance amongst vertical fused filament fabricated specimens via four different printing methods, R. Davies *et al.*, Polymer International, 6172 \(2021\).](#)

[Slow and fast crystallising poly aryl ether ketones \(PAEKs\) in 3D printing: crystallisation kinetics, morphology, and mechanical properties, N. Yi *et al.*, Additive Manufacturing, 39, 101843 \(2021\).](#)

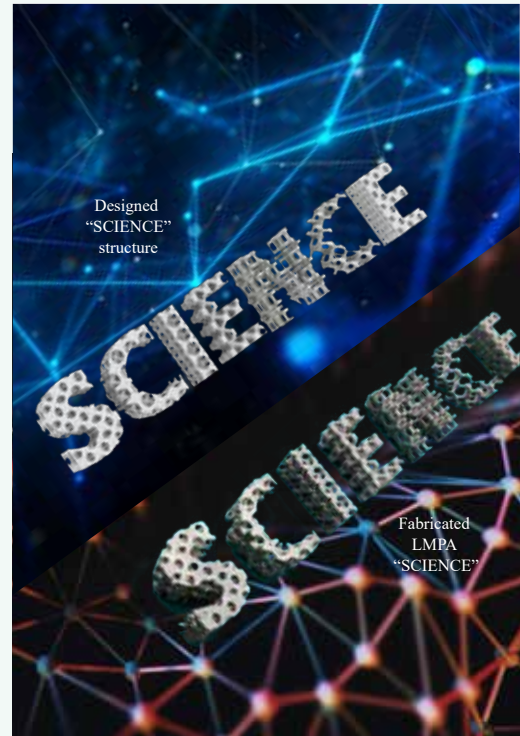
Image of a sintered layer of carbon fibre reinforced PAEK.



Case study: Low-melting-point alloys for additive manufacturing

Complex Low-melting-point alloy products have been successfully fabricated using additive manufacturing with good qualities.

Generic research description: Additive manufacturing has developed significantly. In contrast to established fabricated materials, low-melting-point alloys (LMPAs) are increasingly attractive because they have favorable electrical/thermal conductivities and mechanical strengths. However, LMPA additive manufacturing is still in its infancy. We report a novel strategy for fabricating the complex and/or multifunctional components of LMPAs by extrusion additive manufacturing with two nozzles (for extruding the polymer and for extruding the LMPA). The proposed strategy was used to successfully fabricate complex LMPA components for the first time. We fabricated LMPA/polymer composite parts with improved mechanical properties, and implemented the integrated manufacturing of circuits and 3D products. This will enable the use of LMPAs in applications such as smart structures, electromagnetic shielding, biomedicine, thermal management, energy harvesting, and advanced electronics.



Designed “SCIENCE” structure and its 3D Printed counterpart using low-melting-point alloys.

Case study: Using Weight-Saving plastics to Replace Metals in Automotive

Aim: To explore a new and ground-breaking manufacturing route for thick section thermoplastic composites, particularly PEEK/Carbon Fibre moulding compounds, with the aim of establishing a new and exciting, cost-effective method of making large, bulky, thick section components in order to replace dense metal cast and forged components - the next frontier in the application of composite structures.

High-performance composite systems like Polyaryletherketones (PAEKs), demonstrate exceptional mechanical properties, chemical resistance, and thermal stability. These materials present as a viable lightweight alternative to steel and aluminium, can be moulded and machined at much lower temperatures requiring less energy.

Challenges: The major challenge hindering the rollout of composites for large components is the problem of mould quality where the occurrence of voids within structures causes mechanical weakness. A three year investigation by Exeter researchers has now elucidated the key morphology and processing factors that led to voids and how to avoid them.



Examples of Thick section composite mouldings produced at Exeter. A) composite wheel hubs, these designed for the AgustaWestland AW139 helicopter, B) A composite automotive brake calliper mounted on Exeter's test rig ready for evaluation. C) CT Scan of an early wheel hub prototype- the dark lines are internal voids. The hub section and corresponding CT scan is shown on image D.

Case study: Advanced Full-Composite lightweight brake pads for Automotive

Almost all the world's brake pads across every sector of automotive currently use mild steel as a backing plate. The plate provides structural support for the friction lining material ("pad"). The pad is hot pressed directly onto the steel plate. Exeter has developed a polymeric composite composed of a high thermal stability polymeric resin reinforced with fibres (e.g. glass or carbon). The design is unique in employing a "sandwich" structure. The outer layers are formed from high content fibre layers, whilst the middle is formed from mouldable mid-fibre length grades, where this combination not only provides the required thermal and mechanical properties but also significantly reduces the cost. The unique attributes of our plate technology are as follows:

Lightweight -70% lighter than steel equivalents, thereby reducing un-sprung mass - critical in that it has several times the impact on range and performance of 'sprung' mass mounted inboard of the suspension. Also, un-sprung mass savings enable chassis designers to safely remove weight from the sprung mass without affecting ride quality or safety.

Corrosion Free Thus, potentially removing the need to replace brake pads over a vehicles' lifespan. This especially applies to EV's where regenerative braking accounts for 90% of EV braking scenarios, however foundation Brakes remain a safety-critical component that must work in the absence of Regen. The low usage cycle in foundation Brakes has seen a resurgence in corrosion-induced delamination of the lining from the steel backplate (rust-jacking). This is now an industry challenge, with serious safety implications.

Thermally Insulative 65x less conductive than steel thereby protecting the brake calliper seals from thermal damage (leakage) and preventing brake fluid boil - a catastrophic failure mechanism for braking systems.

Noise Vibration and Harshness (Nvh). Combatting brake-related NVH issues is an industry headache, NVH being No. 1 reason behind customer dissatisfaction. Brake squeal often emanates from the steel backplate, where our CBP's are non-resonant in the audible range and tuneable.

Emissions CBPs don't need sealing paint, the flaking of which, combined with the rusting of steel plates contributes to non-exhaust particulate emissions, where, next to tyres, brakes are now the biggest contributor - an area soon to be heavily regulated in the Euro 7 emissions standards due in 2025.



Composite pads for (Left) racing callipers and (Middle) typical multi-pot callipers. Demonstrator Brake pads have recently been manufactured to commercial standards, including all finishing activities, in a trial with a global pad manufacturer.

Centre for Metamaterial Research and Innovation

Novel solutions for today's technological problems;
new science for tomorrow's challenges.

Find out more
about the CMRI:



About us

The Centre for Metamaterial Research and Innovation (CMRI) is a community of academic, industrial, and governmental partners that harness research excellence from theory to application, and enables simulation, measurement, and fabrication of metamaterials and metamaterial-based devices.

Our breadth is our strength: we are uniquely positioned to solve multi-faceted research questions and industry challenges. Our academic expertise spans electromagnetism (from visible and infra-red through to THz and microwave), acoustics and fluidics. The materials we work with have wide application, e.g., imaging, sensing, and spectroscopy, acoustic and RF signature reduction, energy storage and harvesting.

We believe that excellence in research and impactful science comes from great collaboration and networking. Our long-standing experience in working with industrial partners in the ICT, energy, healthcare and defence, security and resilience sectors enables us to provide fit-for-purpose collaborations, adjusted to the needs of a variety of businesses, from SMEs to large companies.

We work with national and international academic and industry partners, through research projects, PhD studentships and consultancy. As such, our Doctoral Programme with over 30 active PhD Postgraduate Researchers (PGRs) is a core part of the CMRI, developing the next generation of scientific leaders.

Metamaterials: An introduction:

[CMRI - An Introduction to Metamaterials \(youtube.com\)](#)



What are metamaterials?

Metamaterials are structures that are normally made from more than one individual type of material where we can engineer the way they behave by carefully controlling the way we pattern them. It is extremely valuable to be able to do this so that we can design this performance to create the specific properties that we need for an application. Sometimes, and this is the exciting bit, we can derive properties that simply don't exist in the natural world.

Metamaterials are about designing functionality into materials. The enormous range of opportunities that metamaterials offer, controlling sound, light, mechanical vibrations, and heat, have a fantastic range of everyday applications solving global and societal challenges.

What can metamaterials do for you?

Metamaterials find application by using different classes of materials across a variety of industrial sectors. Our case studies for energy, ICT, health and defence, security and resilience over the following pages demonstrate how metamaterials can help modern society to fight cancer, save energy, and protect people and goods.

Our expertise

In different classes of materials:

Biomaterials

The development and characterisation of biomaterials and soft materials for the life sciences.

Case study: Our research into fighting cancer with Terahertz radiation. (see Health case study).

Magnetic materials

The excitation dynamics of magnetic order in structures magnetic materials, and their relevance to data storage, electromagnetic control, electronics, spintronics and magnonics.

Case study: Our work on ESE tags and how metamaterials can protect merchandise where standard security tags fail.

Nanocomposites and novel dielectrics

Engineering of materials and interfaces to enhance electrical, thermal, electromagnetic, and mechanical characteristics, for energy creation, storage and conversion, electromagnetic field control, and catalysis.

Case study: How we communicate in a crowded electromagnetic environment – how metamaterials can give us more space.

Phase change materials

Exploiting switchable electrical and optical properties of phase change materials for photonics, neuromorphic computing, displays and data processing and storage technologies.

Case study: Electrical displays that needs (almost) no power.

2D materials

The extraordinary electrical, thermal, mechanical, and optical properties of few-atom thick materials, and their application to optoelectronics, electronics, photonics, construction materials, energy, and sensing.

Case study: Wearable electronics – from internet of things to human-machine interfacing.

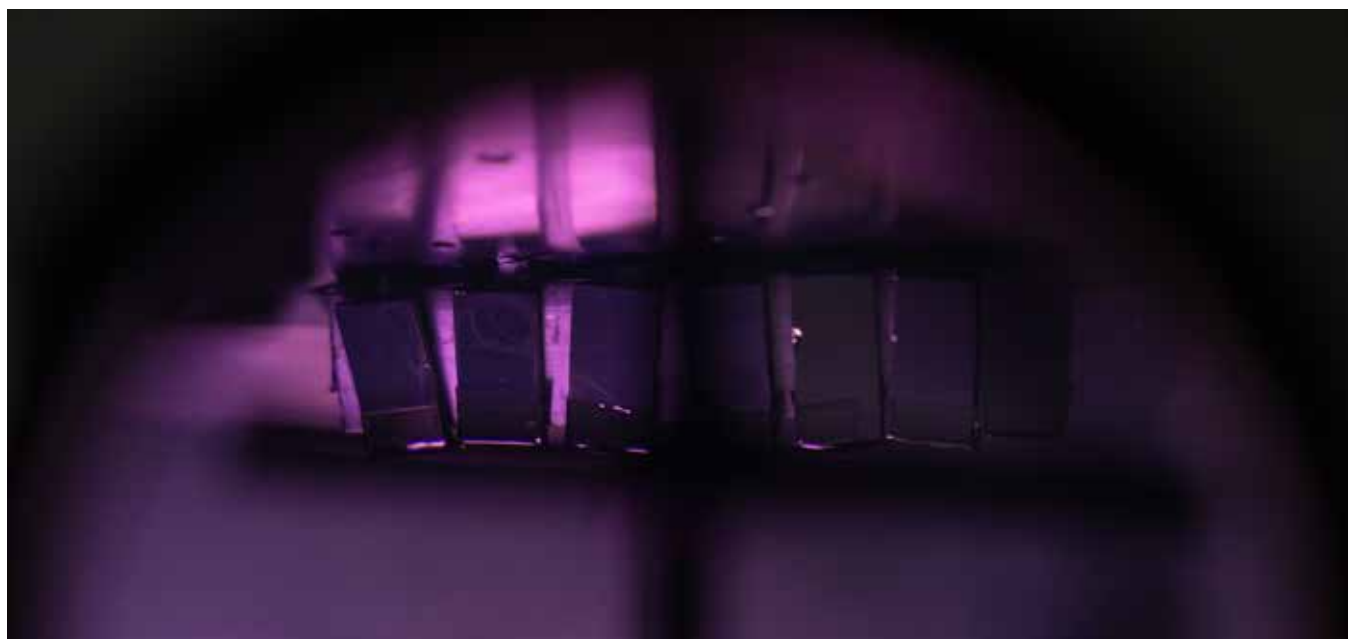
Our expertise

Across industrial sectors:

Our long-standing experience in working with industrial partners in energy, health, ICT, and defence, security and resilience sectors enables us to provide fit-for purpose collaborations, adjusted to the needs of a variety of businesses, from SMEs to large companies.

Energy

Engineering and characterisation of improved materials to harvest, store, transmit, and save energy.



Case study

Investigating the need for sustainable energy, a team within the CMRI focuses specifically on solar panels as one key solution. The ideal solar panel would be highly efficient, lightweight, cost, and carbon effective. They also need to be able to be applied in any orientation or any environment. The key applications for this technology are in areas like building integration, smart structures, and electric vehicles, all of which present a need for a higher power density. Lots of sectors are trying to reduce their carbon footprint and solar photovoltaics are one of the few renewable energy technologies that can be utilised on sub mm areas up to km sized fields.

Currently solar panel technology is either efficient but expensive, or lightweight and less powerful. The goal is to combine high efficiency with lightweight compact panels and introduce multifunctionality.

This looks at solar concentrators which are a combination of optics with solar cells. Within this, there is a focus on nano-structured optics, or metamaterial optics. One of the areas of interest is in bio mimicry where the optical properties of butterfly wings and moth eyes can be explored with regards to the management of light and hence solar panel performance.

This metamaterials science is successfully increasing performance, minimising use of materials and reducing cost in the energy sector.

CMRI Energy Case Study:
[CMRI - Energy \(youtube.com\)](#)



Health

From antibiotic therapy and targeted drug delivery to cancer detection and novel microscopy techniques.

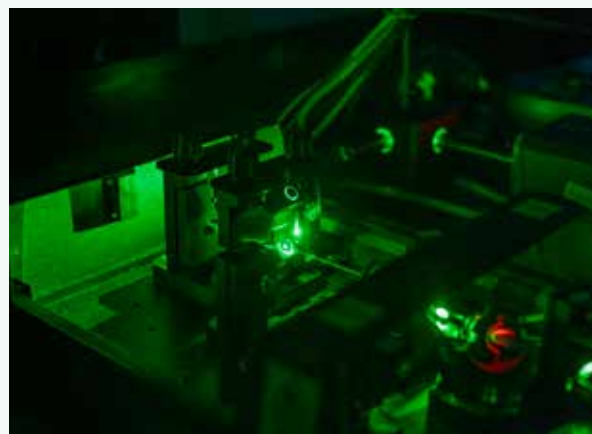
Case study

As part of our research, we are looking at measuring cancer tissue margins. During surgery it is often difficult to tell what is cancerous and what is not. Surgeons take a margin of healthy tissue for safety, but sometimes too much or too little is taken, and this can cause complications or, quite often, a need for secondary surgery to remove excess tissue.

Histopathology normally measures the tissue margin after surgery. However, this only tells the surgeon after the fact whether the margin is correct or not. What is really needed is something that can measure tissue margin within the theatre. What can be used to do this is terahertz radiation. It is safe and could be used in theatre. However, terahertz cameras do not currently exist! To solve this problem, we started to build our own terahertz camera using powerful lasers in the laboratory here at Exeter.

The metamaterial science allows us to miniaturise the building of this camera using much smaller lasers, making it suitable for applications such as this.

CMRI Health Case Study:
[CMRI - Health \(youtube.com\)](#)



ICT: Information and Communication technology

Management of signals and digital data: From processing, modulation, and transmission to absorption and storage.

Case study

All our IT infrastructure, including the internet and all personal computers, use a lot of energy and that is only increasing. So, the problem we are trying to solve is essentially making computers faster and more efficient with a much-reduced energy cost.

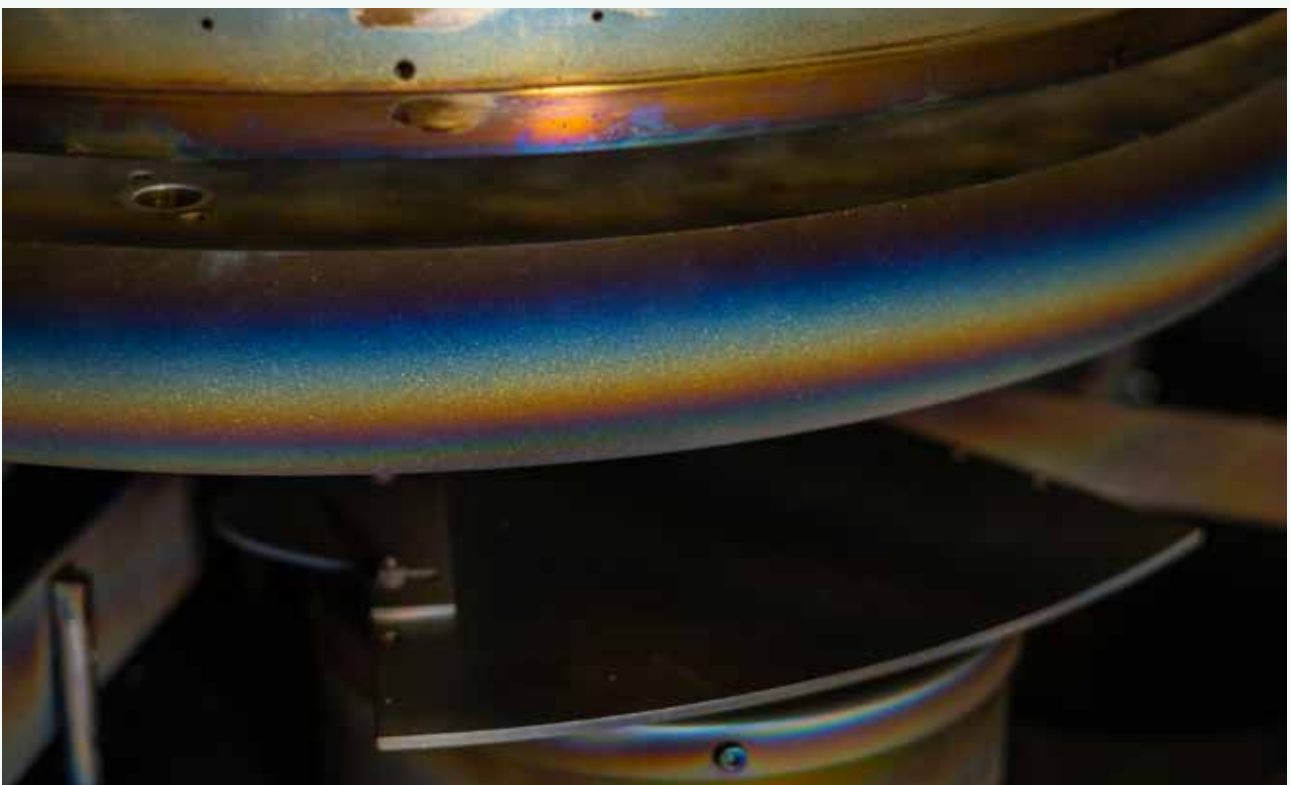
The existing state-of-the-art in computing is the von Neuman architecture which keeps the computation elements, and the memory and data storage separate. This means there is a lot of wasted energy in the transfer of data. This is called the Von Neumann bottleneck, and we are trying to overcome it by inventing new types of computing where everything happens in the same place - a bit like the human brain!

One example of what we are looking at as a solution is a matrix vector multiplier chip, where

the co-location of the memory and computations is possible. This chip could potentially be up to 100 times as fast as existing chips. We are also investigating the use of optics instead of normal electronics for performing computations faster and more efficiently. Metamaterials play an important role in this, whether it is to make devices smaller or creating surfaces and devices that have new and interesting responses to light.

This metamaterial science will enable an increased efficiency and speed at which computations can be done.

CMRI ICT Case Study:
[CMRI - ICT \(youtube.com\)](https://www.youtube.com/watch?v=CMRI-ICT)



Defence, security, and resilience

Materials for acoustic, biological, chemical, and electromagnetic applications to protect goods and people.

Case study

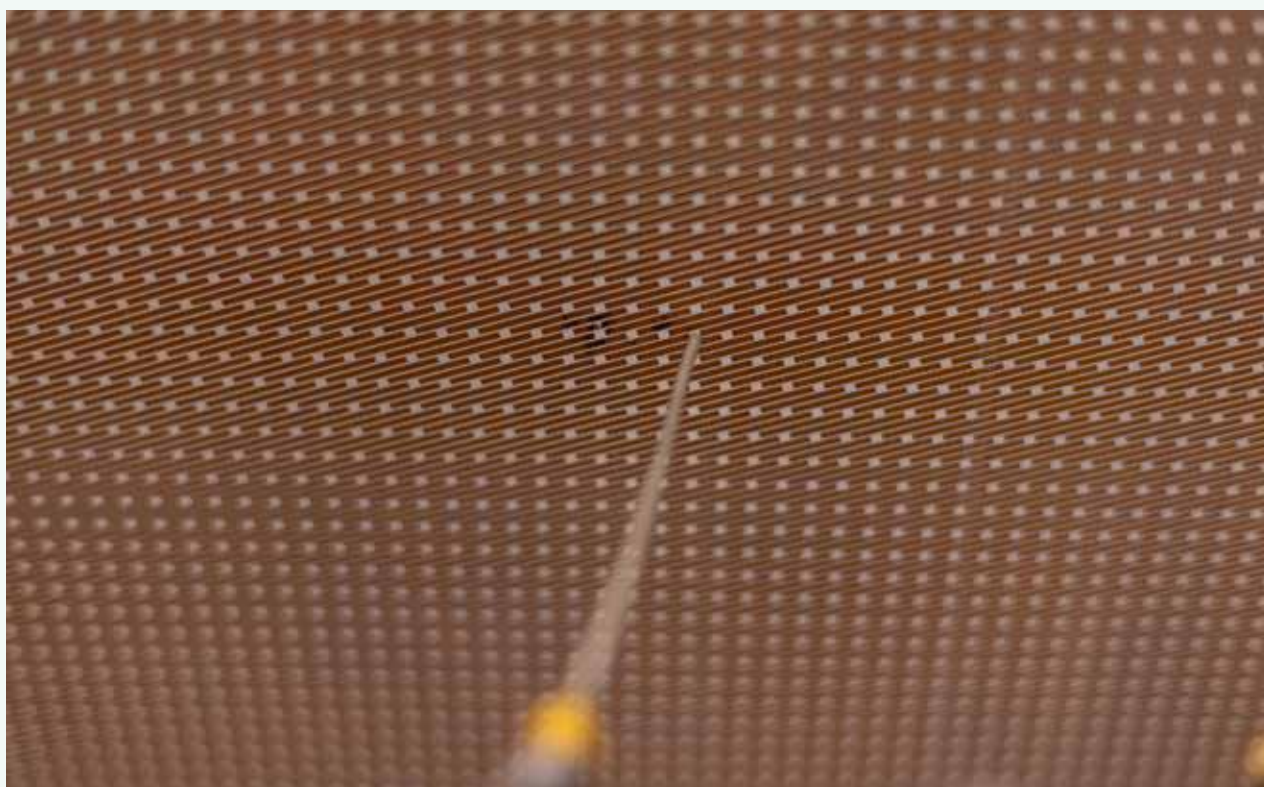
There is a huge array of challenges in the fields of defence and security that metamaterials can make a big difference in. Challenges such as communication in congested and contested electromagnetic environments, control over radar or sonar signatures, active health monitoring or mechanical performance of devices and materials. Metamaterials can be developed to address these challenges, offering solutions that are lighter, faster, more compact, and adaptable than conventional approaches.

At Exeter, we work in something of a unique way. We look at developing the fundamental physics and associated science that will enable these technologies and then passing them on to our partners who can apply it where it can be most useful. Using our full suite of testing facilities for

electromagnetics and acoustics, we develop new metamaterials from first principles, work with collaborators around the UK to fabricate and test them and then often demonstrate a simple use case showing the potential of what we have created.

This metamaterial science is expanding boundaries of what is possible in this field supported with a close working relationship with our partners who need and want these technologies.

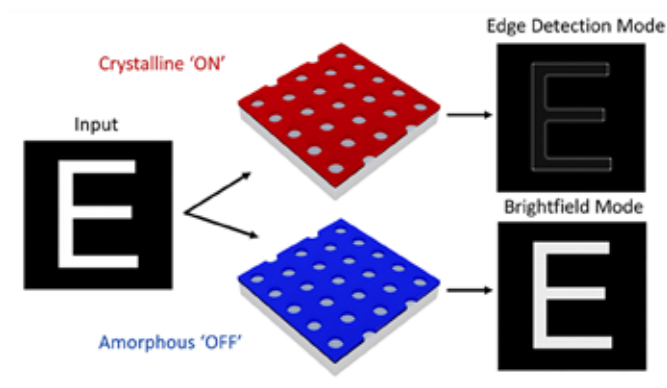
CMRI Defence, Security and Resilience Case Study: [CMRI - Defence \(youtube.com\)](#)



A-Meta

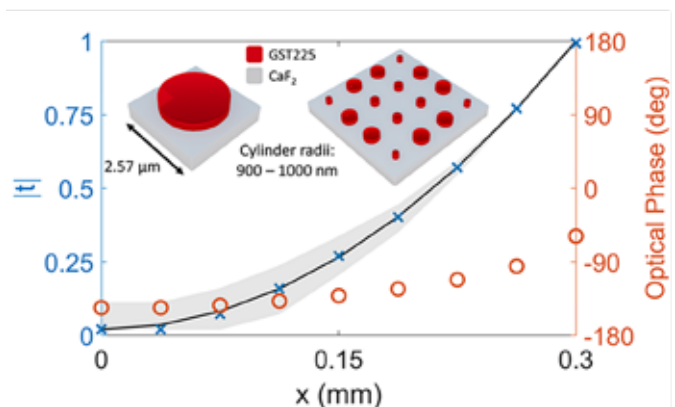
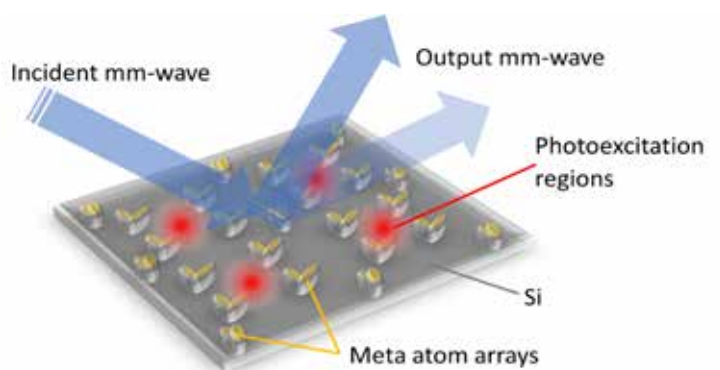
Research Challenge 1:

Analog optical computing has seen an increase in attention in recent years due to potential advantages it holds over its digital counterpart, including intrinsic parallelism, low-loss transmission and ultra-high bandwidth. Fast and energy efficient optical computing systems have been demonstrated, for example implementing neural networks and matrix-vector multiplication. In A-META we are developing metamaterial-based optical computing systems for a range of computational tasks, including image processing, matrix-vector multiplication, optical mode conversion and more. Specifically - along with A-META collaborators at the City University of New York, the University of North Carolina at Charlotte and the University of Oxford - we have developed novel convolutional optical computing approaches using active phase-change metasurfaces that enable emerging applications in artificial intelligence-assisted imaging and vision devices with switchable multitasking.



Research Challenge 2:

We are addressing the lack of practical microwave and terahertz modulators by exploiting the change in conductivity of a semiconductor upon illumination with an optical light source by a novel approach to reduce charge carrier recombination. Fast, high-resolution, and efficient GHz-THz spatial light modulators will be transformative to a new generation of reconfigurable complex systems for imaging, communications, beam steering and more.



Find out more about A-Meta:



Meta-4D

The University of Exeter will play a pivotal part in a new collaboration to lead new research into manipulating metamaterials in the fourth dimension: **time**.

Experts from Exeter's Centre for Metamaterial Research and Innovation (CMRI) will play a key role in a new consortium, called Meta4D, to study

the manipulation of waves, such as light waves or acoustic waves, using tailored metamaterials that vary in time instead of space.

Find out more
about Meta-4D:



Graphene metamaterials for radiation shielding

We are pioneering novel radiation shielding solutions to enhance radiation protection for space systems, ensuring resilience in demanding environments and applications extending beyond the realms of space, including defence, nuclear, and energy sectors.

We are currently developing advanced metamaterials aimed at protecting satellites and reinforcing electronic and radio frequency systems, enabling them to withstand the demanding conditions of space environments. Beyond the space sector, this versatile technology finds applications in Defence, Nuclear, and Energy domains, enhancing the resilience of critical systems, and survivability of personnel. One notable metamaterial we have pioneered involves an alternating configuration of graphene and FeCl₃ monolayers. The material, also designed for use as a transparent electrode in flexible electronics, displays, solar panels, and sensors has showcased significant improvements in both electrical and thermal conductivity properties over either graphene or FeCl₃ materials alone. Moreover, our metamaterial exhibits enhanced resilience against harsh environmental factors, including extreme temperatures spanning from 278 milli-Kelvin to 873 Kelvin. Additionally, it demonstrates exceptional

stability when exposed to oxygen, moisture, and extended periods of high humidity, making it ideal for demanding environments related applications. Through our continuous efforts in metamaterial development, we are aiming to create innovative solutions that advance the capabilities of space technologies. Having already demonstrated a multitude of resilient properties in terrestrial environments, our goal is to establish the immense potential of this metamaterial as a crucial solution for radiation mitigation and charge dissipation on satellites. The exceptional characteristics of this metamaterial offer a promising avenue for effectively countering Total Ionizing Dose (TID) and Single-Event Effects (SEE) arising from on-orbit threats as well as exposure to space, cosmic, and solar radiation across various orbital trajectories. By harnessing the unique properties of this metamaterial, we envision addressing critical needs in space exploration, ensuring the robustness and protection of sensitive equipment and spacecraft in the face of challenging radiation conditions. Our research aims to validate its effectiveness as a coating to safeguard against the effects of radiation, providing significant benefits to the durability and longevity of space missions.

GraphExeter is a patented graphene metamaterial involving alternative layers of ferric chloride (FeCl₃) and graphene (ranging from 2 to 10 graphene layers).

Find out more about
GraphExeter:



The UK Metamaterials Network (UKMMN)

Making the UK a Science and Innovation Leader
in Metamaterials.

Find out more
about the UKMMN:

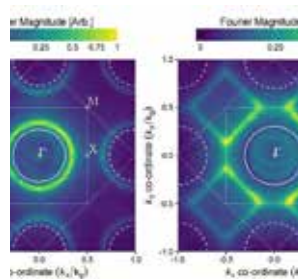


The UK Metamaterials Network (UKMMN) brings together over 800 experts from academia, industry, and governmental agencies to resolve interdisciplinary challenges for this exciting field of materials from theory, fabrication, experiment, to large-scale manufacturing and field testing. Recently, the Engineering and Physical Research Council (EPSRC) awarded £2.5m to the Network to help grow a national metamaterials ecosystem and facilitate the development of innovative metamaterials through pump prime funding. The Network also nurtures the UK metamaterials landscape through advocacy work, facilitation of access to metamaterial experts and facilities (with our free-to-join Membership Database) and interacting with end-users at events to stimulate external investment in metamaterials research.

Led by the University of Exeter and the University of Warwick, the Network is headed by an Executive Board with additional expertise provided by the Leadership Team and External Advisory Board with members across universities and industry to provide a diverse range of experiences and research areas to represent the breadth of the field.

The UKMMN is structured around Special Interest Groups (SIGs) dedicated to fostering relationships around specific research areas, Forums which provide a platform for cross-SIG interactions, and Challenge Areas devoted to investigating the potential of metamaterials to provide practical solutions to global societal challenges.

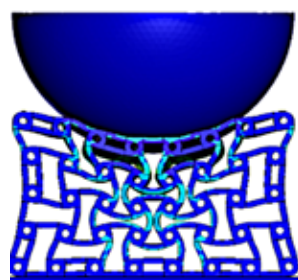
Special Interest Groups



Acoustic Metamaterials



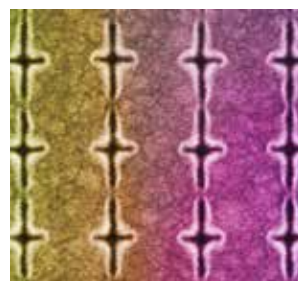
Active Metamaterials



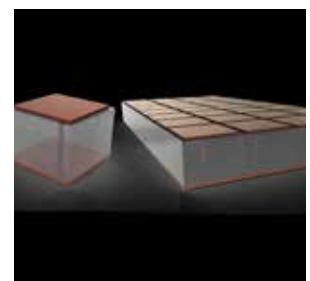
Mechanical Metamaterials



Theory and Modelling



Photonic Metamaterials



Microwave and THz Metamaterials

Challenge Areas



Health



Space & Aviation



Manufacturing & Scale Up



Sustainability

Exeter Innovation

This Department within the University of Exeter can connect you to our world-leading research, expertise and facilities. Whether you are a large corporate, NGO or Government tackling global challenges, a smaller business or charity, or you are just starting out on your entrepreneurial journey, we will have a range of solutions on offer.

We work with many companies – from large multi-national corporations to SMEs, and we have the flexibility and agility to partner each business to their requirements. We offer multidisciplinary approaches in solving research questions and addressing R&D challenges.

Collaborations can range in scale – from a group of our final year undergraduate students working for a few months on a project, to a long-term relationship focussed on a portfolio of significant problems involving several staff, students and facilities. We are always looking for innovative ways of collaborating. Some of the schemes are mentioned below:

- **Knowledge Transfer Partnerships:** A KTP is a collaborative project between a business and the University, which is facilitated by a high-calibre graduate (KTP Associate). The KTP Associate transfers knowledge between the academic team and the business. This scheme is partially funded by InnovateUK.
- **Consultancy & Contract Research:** Consultancy involves a high degree of intellectual input from the relevant academics to the client without the creation of new knowledge. Contract Research targets specific R&D challenges set by the company.
- **Student projects:** Every year we support short duration projects for the final year students, and we encourage companies to support via industrial supervision.

- **Strategic Partnerships:** We maintain several long-term relationships with companies where we develop a substantial portfolio of collaborative work. Over many years, these partnerships have resulted in substantial enhancements, both for the company and the University. We develop and optimise new products, support applications & services, and ultimately the growth of both organisations and their people.
- **Centres for Doctoral Training:** The CDTs support the development of products and services and draw upon facilities and expertise within the University. One of the main drivers for the EPSRC in creating the doctoral training model has been the desire to put industry at the forefront in the development of postgraduate projects for students.
- **Industrial PhD studentships:** The postgraduate student researches a challenge directly relating to the needs of the industry partner.

If you would like any further information about our Advanced Materials research capabilities or would like to work in partnership with the University of Exeter, please do not hesitate to contact us. Connect with our team today:

Call: 01392 723303

Email: innovation@exeter.ac.uk

Address: Innovation Centre, University of Exeter, Streatham Campus, Exeter, EX4 4RN.

Find out more about
Exeter Innovation:



Let's Work Together

Contact our expert team to navigate the University.
Get the right conversation started with the right researchers,
to build the solutions you need.

Email: innovation@exeter.ac.uk

Web: exeterinnovation.com



Exeter
INNOVATION