The vision of the IeMRC was to be the UK’s internationally recognised provider of world-class electronics manufacturing research. It focused on sustaining and growing high value manufacturing in the UK by delivering innovative and exploitable new technologies through its highly skilled people and by providing strategic value to the electronics industry.
Overview of the Innovative Electronics Manufacturing Research Centre

The IeMRC was established in 2004 to provide the UK’s electronics manufacturing sector with access to world-class academic research.

Our academic partners closely engaged with industry in developing new products, processes, industry practices and an increasingly valuable skills base from which they supported high value-added manufacturing in the UK.

Established in 2004
The IeMRC received an initial £5.6 million support for 5 years from the Engineering and Physical Sciences Research Council and delivered 24 projects at 21 institutions across the UK, ranging from ‘blue-sky’ research through to knowledge transfer projects designed to further enhance the impact of the research to the benefit of UK industry.

Following an international review the Centre secured a further £10 million up to 2015 to commission new research projects that continued to deliver to its vision.

Novel Approach
The IeMRC did not follow the standard model for an IMRC, where the research activity was located at a single or pre-defined group of institutions. Rather, the IeMRC established an end-user oriented ‘Virtual Centre’, consisting of a number of institutions collaborating under a central ‘hub’ and a core management structure.

Research Themes
The IeMRC research themes were chosen specifically to draw in a large number of academic researchers from a wide variety of disciplines and backgrounds throughout the UK. The themes also echoed the breadth of EPSRC’s portfolio and, in all cases, the IeMRC funding formed only a part of the recipients’ research portfolio.

- Manufacturing business processes
- Sustainable manufacturing
- Products and processes
- Challenging environments: new application areas
- Materials, manufacturing processes and technology

Engagement and Impact
Throughout its lifetime, IeMRC research engaged 95 different academics and supported research staff that amounted to 32 research associates, 25 PhD research students, 4 technical and support staff, all spread across 30 institutes. The groups engaged 153 different companies in their research projects.

The Executive
The IeMRC executive function was shared between seven universities and provided a focus for the Centre that was distinct and separate from the supported research activities.
## Themes Addressed by the IeMRC

<table>
<thead>
<tr>
<th>Theme</th>
<th>Vision</th>
<th>Research Issues Addressed</th>
</tr>
</thead>
</table>
| Manufacturing business processes           | To address the aspects of managing products for life, in particular the through life implications from the concept design stage to in-service. | • Through life management  
• Supply chains  
• Cost Management Through Life  
• Uptake of disruptive Technology  
• Innovation  
• Legislation  
• Business Modelling |
| Sustainable manufacturing, products and processes | To meet the needs of the current generation without compromising the ability to meet the needs of future generations. For the electronics sector, this means designing and developing new technologies that underpin continued growth while using more innovative materials, less energy and generating less waste and complying with environmental legislation. | • Energy  
• Green electronics  
• Single unit manufacture  
• Sustainable manufacture  
• DfAssembly  
• DfDisassembly  
• Process control  
• Partitioning  
• Power management  
• DfRecycling  
• Business modelling |
| Challenging environments: new application areas | To provide underpinning research that will enable the UK electronics industry to retain its competitive edge in high added value sectors such as healthcare, aerospace and energy, where there are significant demands for sophisticated electronic products that can operate reliably in new or challenging environments. | • Security  
• Low volume DfM  
• Thermal management  
• Integrated optics  
• Reliability  
• Test data for reliability  
• Qualification strategies  
• DfManufacture (DfM)  
• Multi-physics tools  
• Harsh/new environments |
| Design for X                               | To provide underpinning research into design methodologies that will enable the UK electronics industry to retain and enhance its competitive edge in high added value and low-volume sectors. Objectives for this theme are to deliver research into design methods that support existing strengths and underpin the development of future markets for UK electronics and to support other IeMRC themes in developing solutions in challenging environments. | • Test strategies  
• Collaborative design  
• Partitioning  
• Multi-physics tools  
• High frequency  
• DfAssembly  
• DfDisassembly  
• Power management  
• DfRecycling  
• Thermal management  
• Reliability  
• DfManufacture  
• Low volume DfManufacture  
• Tests for reliability |
| Materials, manufacturing processes and technology | To deliver research in materials, manufacturing processes and technology to secure the future competitiveness of the UK in providing the foundations for new and emerging markets that could be nurtured within the UK electronics community. | • Qualification strategies  
• Packaging power electronics  
• Single unit manufacture  
• Lead-free  
• Direct imaging processes  
• Lean technologies  
• Integrated optics  
• Bio-applications  
• Integrated MEMs  
• Smart materials |
Programme Management

With an operational hub at Loughborough University, the IeMRC’s central location allowed easy interaction with industry and academia across the whole of the UK.

Management and Organisation

The IeMRC had a hub at Loughborough University to manage the operational activities of the Centre. The IeMRC Executive directed the Management Function (as presented in the table below).

The research direction and prioritisation was provided by the Industrial Steering Group (ISG), thereby supplying the consultation function.

These management and consultation functions were embedded in a framework of governance that endorsed the operational processes, ratified transparency of processes and had the authority to impose sanctions if required. The Governance Function resided with the IeMRC Board of Governors.

The reporting structure of the IeMRC

The Academic Director reported to the Governors directly and EPSRC. The Coordinator and Industrial Director in turn reported to the Academic Director and the Secretariat provided support to the management and governance functions.

<table>
<thead>
<tr>
<th>Function</th>
<th>Management</th>
<th>Governance</th>
<th>Consultative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Responsible Body</td>
<td>IeMRC Executive</td>
<td>Board of Governors</td>
<td>Industrial Steering Group</td>
</tr>
<tr>
<td>Membership</td>
<td>Principal Investigator (Chair)</td>
<td>Independent Chair</td>
<td>Industrial Director (Chair)</td>
</tr>
<tr>
<td></td>
<td>Co-Investigators</td>
<td>Independent Industrialists</td>
<td>Industrial representatives</td>
</tr>
<tr>
<td></td>
<td>Industrial Director</td>
<td>Independent Academics</td>
<td>Trade Associations</td>
</tr>
<tr>
<td></td>
<td>IeMRC Coordinator</td>
<td>Independent Civil Servants</td>
<td>DTI Representation</td>
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<tr>
<td></td>
<td>Industrial Advisors</td>
<td></td>
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<tr>
<td></td>
<td>Invited Academics</td>
<td></td>
<td></td>
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<tr>
<td>Ex-Officio</td>
<td>EPSRC Secretariat</td>
<td>Principal Investigator</td>
<td>IeMRC Coordinator</td>
</tr>
<tr>
<td>Members</td>
<td>Research Finance Officer</td>
<td>Industrial Director</td>
<td>Principal &amp; Co-Investigators</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EPSRC Secretariat</td>
<td>Secretariat</td>
</tr>
</tbody>
</table>

With an operational hub at Loughborough University, the IeMRC’s central location allowed easy interaction with industry and academia across the whole of the UK.
The IeMRC Industrial Steering Group defined key research priorities based on its extensive knowledge of the needs of the UK electronics industry. This enabled the research priority areas and remits of the IeMRC research landscape to be determined and calls for proposals to be approved by the Chair. The criteria upon which proposals were assessed and the time frame for the call were also set by the Steering Group.

The IeMRC hub operated the process of launching the call for proposals, receipt of proposals, assignment of proposals to reviewers, management of the review process and operation of the subsequent prioritisation panels.

Each call for proposals was disseminated widely through channels targeted at both industrial and academic communities and was a two-stage selection process. The first stage initiated by the publication of the Call for Proposals, invited outline proposals. These were submitted for review against the published criteria by an IeMRC prioritisation panel. Successful outline proposals were invited to submit full proposals comprising a standard EPSRC responsive mode proposal package with an IeMRC equivalent of the eSRP1 form. The overall process for each call was recorded and ratified by the IeMRC Governors prior to publication of the final results. Following the outline stage, there were opportunities for brokerage of consortia in common areas of research. Throughout Phase 1 and 2 there were 11 calls for proposals issued by the IeMRC.

Exceptional projects such as the IeMRC large scale projects e.g. Flagship and Grand Challenge worth >£500k IeMRC funding (or smaller at the discretion of the Academic Director) were subject to additional scrutiny prepared by the IeMRC Executive and ISG also nominated additional members to fill gaps and provide balance across the themes. The membership was refreshed on a continual basis, including the use of proposer’s nominated reviewers. The EMPC was used for assessment of proposals seeking funding as well as assessment of research project outcomes and involvement in Centre-level research audits. Following award of funding, the IeMRC hub monitored all on-going and completed projects. Each project was required to have regular meetings e.g. kick-off, quarterly and a final project review meeting. The meetings were attended by the IeMRC Coordinator and/or one or more of the IeMRC Directors (or members of the IeMRC Executive if available and appropriate to the specific project). Each project was also required to submit a final report in order to draw down the last 20% of its funding.

The IeMRC final project reports consisted of completion of a tailored Grant Review Proforma (GRP) and a detailed report. The reporting requirements required grantees, reviewers and those attending a final review to provide assessments of:

- the technology readiness level (TRL) of the research deliverables.
- the level of achieved and anticipated future impact of the research.
- the standing of the research relative to international research standards.

Each year, the IeMRC performed a periodic research audit by collating information for annual and renewal reports as well as for the annual conferences.

Assurance of the quality and international standing of the research themes and projects was provided by the Electronics Manufacturing Peer College (EMPC). This was formed by nomination and selection of internationally regarded peer reviewers, who were engaged to provide independent objective judgement of the IeMRC’s research themes and outputs.

The EMPC was initially formed out of the self-assessment of the research themes during the IeMRC benchmarking exercise in 2008/9. The IeMRC Executive and ISG also nominated additional members to fill gaps and provide balance across the themes. The membership was refreshed on a continual basis, including the use of proposer’s nominated reviewers. The EMPC was used for assessment of proposals seeking funding as well as assessment of research project outcomes and involvement in Centre-level research audits. Following award of funding, the IeMRC hub monitored all on-going and completed projects. Each project was required to have regular meetings e.g. kick-off, quarterly and a final project review meeting. The meetings were attended by the IeMRC Coordinator and/or one or more of the IeMRC Directors (or members of the IeMRC Executive if available and appropriate to the specific project). Each project was also required to submit a final report in order to draw down the last 20% of its funding.
Facts and Figures

The EPSRC centre award was £15.6 million over 10 years supporting the research of 95 academics, 25 PhD studentships and 32 research associates.

IeMRC research grants funded totalling £12.6 million over 92 research projects ranging from £20k feasibility studies to £2 million flagship projects.

153 industrial sponsors invested in research: with UK industry providing £4.7 million, £185k from European sponsors, and £148k from international companies.

2004 - 2015:

Distribution of Funding Against Centre Themes

Northern UK:
IeMRC funding £2.4 million
Industrial sponsorship
£1 million

Central UK:
IeMRC funding £6.2 million
Industrial sponsorship
£1.6 million

Southern UK:
IeMRC funding £4 million
Industrial sponsorship
£2.1 million

Manufacturing Business Processes
Sustainable Manufacture, Products and Processes
Challenging Environments: New Application Areas
Design For X
Materials, Manufacturing Processes and Technology
Impact

1 Government Policy Influenced
“Power electronics: a strategy for success”

“I believe that the IeMRC has been the catalyst for some excellent research work with direct relevance to industry. Furthermore, it was a key element in the process which led to the Department for Business Innovation & Skills issuing the document POWER ELECTRONICS: A STRATEGY FOR SUCCESS. An important milestone in the recognition of the strategic importance of Power Electronics to "UK Ltd." and a springboard to its greater success.”

Graham Ferry
IeMRC Industrial Steering Group

4 Spin Off Companies
7 Books
7 Technical Reports
8 Patents
49 Promotional and Network Events

150 Journal Papers Published
229 Conference Papers Disseminated
305 People Engaged
Case Study

Functionalisation of Copper Nanoparticles to Enable Metallisation in Electronics Manufacturing – CuNano

Investigators:
Dr Andrew Cobley, Dr John Graves - Coventry University and Dr David Hutt - Loughborough University

Context and Project Aim

An underpinning technology within the electronics industry is the requirement to metallise dielectric materials to form conductive tracks and vias for interconnection on a range of substrates such as PCBs, ceramics, and plastics. Electroless copper metallisation is widely used but, due to the variety of substrate materials, presents challenges in terms of surface modification and adhesion.

Typically, the electroless plating process requires the deposition of a catalyst layer to provide a seed on which the copper can nucleate and grow and most metallisation processes utilize precious metals, especially Pd colloid nanoparticles, for their catalytic properties. The continued use of such metals is problematic in terms of their expense, scarcity and resource efficiency.

The overall aim was to take commercially produced copper nanoparticles (CuNPs) and develop techniques for their functionalisation with organic molecules. These were then to be used:

- As low cost catalysts for electroless copper plating and thus replace expensive palladium based catalysts;
- To produce ink-jettable patterns for printed electronics and provide a low cost alternative to silver loaded conductive inks which contain a high metal loading;
- As a conductive layer for ‘direct’ electroplating of through holes in printed circuit board (PCB) manufacture.

The outcome of this project laid the groundwork for the formulation of a series of catalyst inks based on an abundant metal - copper.

The ultrasonic dispersion of a copper nanopowder has been benchmarked, and methods for the functionalisation of particle surfaces with organic coatings have been shown to be effective to protect the copper layer from oxidation, yet still initiate electroless copper deposition.

Further work is required to improve coverage and adhesion to substrates, but the concept of using copper based catalysts to metallise non-conducting substrates has been demonstrated.

The research has also demonstrated the potential to functionalise particles selectively in order to introduce specific chemical groups that are expected to interact effectively with specific substrates. Further research could therefore enable the development of substrate specific catalyst systems that could eliminate the need for harmful substrate pre-treatments presently used with the traditional Pd/Sn colloid system.

In addition to advances in PCB metallisation, in the long term, the Printed Electronics Industry will also benefit from the development of a low cost manufacturing process which avoids the use of expensive silver inks and a sintering process for the formation of conductive tracks.

A process based upon catalytic copper inks has the potential to reduce energy requirements and
Case Study

**Duration:** 2010 to 2015

**IeMRC Funding:** £334,608

2 Academic Partners
4 Supporting Partners
1 Publication/IP
10 Dissemination Events

opens up the opportunity to use temperature sensitive substrates and therefore affords new applications of printed electronics.

The UK and EU dependence on a number of critical materials has been highlighted in a series of recent reports and there is a co-ordinated effort to reduce the usage of such materials. The potential to replace precious metals in catalytic seed layers with more abundant copper is a significant outcome of this research project.

Outcomes

The outcomes from this research are therefore both timely and highly relevant.

A recent, direct consequence is the invitation to Dr Cobley to attend a CRM (Critical Raw Materials) workshop (organised by the CRM InnoNet project consortium and funded by the 7th Framework programme) mapping out a substitution roadmap for the replacement of CRMs in printed circuit boards.

The Future

In keeping with the research themes described in the introduction, funding opportunities are being pursued to progress this work in other application areas where it is possible to substitute critical materials with functionalised copper based products. Two EU H2020 proposals were also submitted.

In addition, LENFF funding has been secured for additional equipment and technician time on a Bruker Multimode 8 AFM in the Leeds Nanoscale group to continue work that was started in this project. It is hoped that this will lead to a joint paper on substrate modification pre-treatments.

A further peer reviewed paper based on the results of this project is also planned for publication at this stage: Characterisation of functionalised copper nanoparticles as catalysts for electroless copper plating.

FR-4 (a) activated with APTS functionalised CuNPs

(b) after electroless copper metallisation.
Soldering is a key process of electronics manufacture and involves the formation of a mechanical joint between a solder (usually tin based) and a metal substrate. This is the method by which the vast majority of components are connected mechanically and electrically to printed circuit boards (PCBs) and, given the increasing complexity of electronic products, the reliability and effectiveness of these electronics systems are of vital importance.

The strength of the joint is related to how well the substrate and solder are able to interact with each other and if any residues are left on the surface they can severely affect the quality of the solder joint. As such, a solder flux is always used to remove any surface oxide and residues on the substrate during the soldering process.

There are a number of environmental and procedural issues relating to conventional solder fluxes. These are often composed of harmful inorganic salts, have batch consistency problems and/or have harmful and acidic additives to improve solderability. In addition, protective surface coatings are added to PCBs and components in order to maintain solderability as the relatively mild fluxes used in the electronics industry poorly solder copper. They can be extremely costly, often including gold coatings. Also, many failure modes of electronic systems involve the brittle fracture of solder joints. This is considerably more likely to happen if the joints are not soldered fully.

This project aimed to investigate, develop and test novel deep eutectic solvents (DESs) as solder fluxes for component and circuit board manufacture. Deep eutectic solvents (DESs) are a novel type of ionic liquid which are composed of an ammonium halide salt and a small organic molecule containing hydrogen bond donating groups. As these two compounds mix together, a large suppression of the melting point is seen enabling the formation of a mixture with a melting temperature below or around room temperature.

These liquids provide an excellent environment for coordinating metal ions enabling high solubility of metal salts including oxides. As such DESs are of interest in a number of different metal processing techniques such as electrodeposition, electropolishing, electrowinning, and recycling.

In the case of soldering, the DESs are highly effective at removing any residual oxide from the surface of a metal enabling excellent substrate-solder wetting. This means that solder joints can form reliably and quickly.

Key Findings

The research project progressed rapidly and saw an excellent level of engagement from project partners, as such there is already considerable impact of this research with greater future potential. It has been demonstrated that the DES fluxes can act as highly effective solder fluxes with certain benefits over the existing methodologies.

Additionally, the physical properties of the flux can be altered through either judicious choice of DES component or the use of an additive to provide the specific properties required. The DESs possess many benefits over existing fluxes, yet they can be engineered to possess certain physical properties, therefore, they could be used as drop in replacements in existing manufacturing methods. For example, a hot air solder levelling (HASL) flux was developed as a part of the work which solders more effectively than the existing ones in use today. This means that HASL coating of PCB panels can be performed using only one immersion in a solder bath rather than two, meaning there is less thermal shock on the PCB, as well as having a more uniform coverage of solder across the surface. As these fluxes can also be used on electroless nickel substrates, something that cannot be done with conventional methodologies, then these substrates can also be used in HASL coatings leading to a new PCB surface finish which has been called HASLEN (hot air solder levelling onto electroless nickel). The HASLEN PCB surface finish is of interest to the PCB and Components industry in order to maintain the reliability and performance.
Case Study

**Duration:** 2013 to 2015

**IeMRC Funding** £224,629

2 Academic Partners
7 Supporting Partners
3 Publications/IP
7 Conference Presentations

electronics sectors as it offers high reliability, particularly where the resulting product will be used in a high temperature environment. This was the subject of a webinar directed at interested industry parties, hosted by ITRI innovation that had high levels of engagement and generated follow on interest from a number of companies.

These fluxes have also been used in the manufacture of a solder paste, which is typically the method of soldering where surface mounting of components is required. The surface mounting of components is a multistep process and it is important that the solder flux performs well through all of these stages. This includes, but is not limited to, effective screen printing of the solder paste onto the PCB, being able to hold components in position when undergoing “pick and place” of components on the circuit board as well as the primary function of soldering the components to the circuit board effectively.

It was found that these fluxes had excellent release characteristics from the stencil during screen printing. There is an increasing drive to smaller feature sizes and components in the electronics industry, and as a result, it is necessary for the solder paste to release onto the PCB from increasingly smaller features in a stencil for screen printing.

The solder paste that was developed in the project was able to release from much smaller apertures than conventional solder pastes. When the screen printed PCB had components placed onto its surface and subsequently underwent solder reflow, solder joints were demonstrated to form very reliably as shown in Figure 1. This was the case for all PCB surface finishes tested, including bare copper and electroless nickel. These solder joints were shown to be void free and uniform throughout.

A solder paste that will work directly on bare copper and/or electroless nickel offers substantial benefits to both electronics manufacture and wider society. No PCB surface finish would be required resulting in a lower cost of PCB, the elimination of electronics failures related to the surface finishing process such as “black pad” and removing the dependence of the PCB industry on some minerals which can come from conflict areas.

**The Future**

The research has been exceedingly well received generating significant interest from related industrial parties. Andrew Ballantyne was awarded a prize for “technology most likely to reach commercialisation” at the R2i meeting in Loughborough 2013. The concept of soldering using deep eutectic solvents has been submitted for intellectual protection and these fluxes are still being developed with the aim of commercial release in conjunction with Qualitek (Europe) and Scionix LTD. The project also obtained an additional £15,000 from the University of Leicester for the commercialisation for the HASLEN PCB surface finish.

Cross sectional images of (a-c) HASL and (d-f) HASLEN coatings after accelerated ageing for 0, 3 or 14 days after ageing at 130°C
Case Study

Roll-to-roll Vacuum processed Carbon Based Electronics (RoVaCBE)

Investigators:
Dr Hazel Assender - University of Oxford, Prof Martin Taylor - Bangor University, Prof Long Lin - University of Leeds, Prof Steve Yeates - University of Manchester

Context and Project Aim

There has been increasing interest over the last decade or so in developing low-cost processes for printing organic thin film transistors (OTFTs) and circuits onto flexible substrates for e.g., display backplanes, security tags and integrated logic on plastic packaging. Organic transistors provide the basis for the development of mechanically flexible electronics with the very low processing costs that can be realised utilising high web-speed roll-to-roll (R2R) production.

Commercial vacuum equipment is already available for applying metal patterns onto plastic packaging. Vacuum processing removes many solvent related issues, e.g. solvent drying times and recovery, solvent-induced layer interdiffusion, pinhole defects and surface roughness, which can lead to poor device performance and low yield, thus negating the suggested cost advantage of solution-based processes. Although such solution-based processes are considered ‘low cost’, it is not self-evident that this is the case.

Environmental costs, coupled with health and safety, considerations dictate that solvent recovery systems must be incorporated in any production line, and the choice of solvents is limited. Any solvents used must be highly purified, solutions must be kept free of extraneous contaminants and, for high performance devices, fabrication must take place under cleanroom and possibly inert atmosphere conditions.

All of these measures will add significant costs to the production process. Initial work prior to the project had established a possible all-vacuum-evaporated route for manufacture of an OTFT, but this project sought to research the manufacturing routes to large-scale production of OTFTs with high, reproducible performance at high yield so as to enable the design and manufacture OTFT-based circuits. Many groups internationally have demonstrated functioning organic transistors on a lab-scale and there have been a few demonstrations of scale-up routes to OTFTs using solution-based organic materials. However, little or no work has been reported from elsewhere on large area vacuum deposition of OTFTs.
Case Study

**Duration** 2010 to 2015

**IeMRC Funding** £1,187,710

4 Academic Partners
10 Supporting Partners
12 Publications/IP
25 Conference Presentations

**Results**

This project was characterised by a very positive and collaborative approach by all the partners, which greatly assisted the progress.

Examples of direct collaboration included the students at Oxford and Bangor working closely together in the laboratory, samples moving between all universities for experimentation, a good supply of synthesised semiconductor from Manchester, supply of materials from Scott Bader, software support from Silvaco, design of oil patterning experiments with GVE, and a host of ideas and suggestions from other partners including Camvac, Axess and, not least, the IeMRC representatives.

The project made excellent advances against all its project aims. It demonstrated:

- A robust manufacturing route to organic transistors
- The design, simulation and fabrication of a range of electronic circuits (digital logic and analog), all on polymer substrates
- R2R-compatible encapsulation and patterning approaches
- Replacement of high cost gold electrodes with lower cost materials

Additionally, bias stress and environmental stress testing of the transistors and circuits was undertaken.

**The Future**

The key ambition, to be able to demonstrate a robust manufacturing process for organic transistors, has been achieved.

A significant number of potential hurdles to commercialisation have been overcome setting up this field for the next stage of investment in integrated manufacture and applications. Significant interest in this work has been expressed by a number of industries ranging from major international companies to SMES. Sectors have included film convertors, packaging, automotive, electronics, equipment manufacture and materials supply. However, even though the project has successfully demonstrated how this manufacturing route overcomes many major obstacles to commercial exploitation such as reliability and yield of transistors, circuit manufacture, circuit design and simulation, an all-evaporated high speed process using low cost materials, stability of resulting devices, and integration with other R2R processes for circuit integration, this has not yet led to investment in the technology or future collaborations.

Some of these key components have only recently been demonstrated, so efforts to further engage with tech transfer and industrial pull-through are still ongoing. The PIs are seeking further academic funding, and, in addition, the PIs are working with CPI, Isis Innovation, and the Welsh Assembly in an attempt to take the development of this technology forward.
Case Study

Carbon Nano Tube (CNT) Composite Surfaces for Electrical Contact Interfaces

Investigators:
J. W. McBride, S. M. Spearing, L. Jiang - University of Southampton

Context and Project Aim

This IeMRC funded project was unique in the international context. It was aimed at addressing a fundamental 20 year old problem of reliability and robustness in metal-to-metal electrical contacts in MEMS switching devices. Whilst MEMS relays boast a number of advantages over PIN and FET devices etc., notably high isolation, low on resistance and excellent frequency performance, one of the major disadvantages of metal-to-metal MEMS relays is that their electrical contacts are known to fail after a number of switching cycles.

With no, or low (<0.5 mA, <0.2 V), electrical load conditions the lifetime may reach into the billions of cycles, however, switch failure occurs sooner with the application of larger electrical loads (>0.5 mA, >1 V).

MEMS relays can be subdivided into two categories: metal-to-metal and capacitive (i.e. varactors). Typically, the latter operates by moving an electrical contact relative to another which has the advantage that the conductive electrodes do not make physical contact.

The operation of the former relies on creating a contact between two electrodes; this has the disadvantage that the contact surfaces are subjected to damage from both electrical and mechanical factors.

The electromechanical mechanisms which cause damage on the electrical contact surfaces for metal-to-metal contacts were considered in this project; in particular, the interaction between a thin film gold contact and an Au/MWCNT bilayer composite.

The cumulative damage on the contact surfaces results in a limitation on the device lifetime. One aim of this work was to discuss potential applications of the Au/MWCNT composite technology and the routes to exploit them.

Results and Impact

The results of the research conducted within this project can have a significant impact on the MEMS relay business. Additionally, there will be spin-offs in the areas of sensors, instrumentation and in the application of CNT surface for other applications. The consortium formed a supply chain and had the potential to fully develop the proposed technology.

The main advantage of this technology is the extended lifetime for a metal-to-metal contacts. An advantage of the metal contact is that it has a low contact resistance. Furthermore, there is potential that the composite contact could be of interest for RF (radio frequency) applications. The field of RF would introduce a number of specific design constraints.

The scientific research has been widely published and the work conducted has been commented upon as an exemplar.
Case Study

Duration 2011 to 2014

IeMRC Funding £293,290

2 Academic Partners

5 Supporting Partners

8 Publications/IP

24 Conference Presentations

Key publishable outputs

- Developed fine transfer model for predicting failure of Au/MWCT composites over range of values for load current and the effect of load current on failure of Au/MWCT composites, in terms of the size of the failure site, cycles to failure and failure mechanisms.

- Produced MEMS developmental cantilever beam to test Au/MWCT composites and demonstrated MEMS switching incorporating the Au/MWCT composite. This was a major achievement and met one of the key objectives of the research. MEMS switched for 44.4 million hot-switching cycles with an electrical load of 4 V and 50 mA. This current level exceeded all published work on “hot switching” of MEMS.

- Complete composite characterisation, including mechanical, coupled with FEA modelling to allow the development of models to predict optimized parameters for the composite.

- Complete mechanical and electromechanical characterization of the influence of each component and varying composition as well as loaded surface profile measurements of Au/MWCT composite surface and evaluated and modelled effect of adhesion layers on the reliability of thin films.

At the IeMRC Research to Industry conference, Jiang (CI) won an award in 2012, and Lewis in 2013, the IEEE award for “potential of technology presented to be commercialised”. A number of informal academic links have been established, which have resulted in International linked publications, both with the USA, Malaysia, and planned with Japan. The informal links have strengthened with research staff exchanges during the duration of the project. Future joint research proposals are planned, USA-UK, and Malaysia-UK.

Angled View of Au-Coated MWCNT Surface. MWCNT forests are grown using thermal CVD. Height varied by altering growth time.
## Project Summary Table: Phase 1

<table>
<thead>
<tr>
<th>Project title</th>
<th>Institutes</th>
<th>(FEC) Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flagship: Power electronics</td>
<td>Sheffield, Nottingham, Greenwich, Manchester, Oxford, Newcastle</td>
<td>£835,199</td>
</tr>
<tr>
<td>Flagship: Optical printed circuit board manufacturing</td>
<td>UCL, Heriot-Watt, Loughborough</td>
<td>£802,867</td>
</tr>
<tr>
<td>Feasibility study: Microemulsion fabrication of nanoparticles for enhanced solder materials</td>
<td>Kings College London</td>
<td>£52,323</td>
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<tr>
<td>Feasibility study: Lithographically printed voltaic cells</td>
<td>Brunel</td>
<td>£52,166</td>
</tr>
<tr>
<td>Feasibility study: Micro-materials integration and evolution in digital electronics manufacturing</td>
<td>Loughborough</td>
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<td>Feasibility study: Challenges for electronic manufacturing posed by new surface contamination related failure modes in the context of the wireless revolution</td>
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<td>Feasibility study: Scoping study of laser patterning of thin-films for high volume manufacture of electrical structures</td>
<td>Hull, Brunel</td>
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<td>Frequency agile microwave open-oven bonding system (FAMOBS)</td>
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<td>Glass substrates for high density electrical and optical interconnect</td>
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<td>Design and simulation of complex low volume Electronics production (DISCOVER)</td>
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<td>Design for manufacture methodology for system in package technology</td>
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<td>Chemically amplified resists for next generation lithography</td>
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<td>Feasibility study: Design tools for the manufacture and implementation of Pb-free solder joints: materials modelling challenges</td>
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<td>Through Life cost estimating within defence systems</td>
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<td>Nanoparticle stabilized solder materials for high reliability applications</td>
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<td>Novel high energy density, high reliability capacitors</td>
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<td>Integrated health monitoring for bio-fluidic systems</td>
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<td>Communication systems for deployment in hostile environments</td>
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<td>The use of advanced sensing technologies for protection suits-enabling safer safety critical manned missions</td>
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<td>Flagship: Roll-to-roll Vacuum processed Carbon Based Electronics (RoVaCBE)</td>
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<td>Flagship: SMART Microsystem</td>
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<td>Thermosonic-adhesive flip chip assembly for advanced microelectronics</td>
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<td>High-performance low-cost power modules for energy smart network applications</td>
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<td>3D microwave &amp; millimetre-wave system on substrate using sacrificial layers</td>
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<td>Electrochemically assisted integration of organic semiconductors on CMOS and</td>
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<td>Micro-interconnects using mono-sized polymer microspheres for large format</td>
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<td>WHISKERMIT: Manufacturing and in-service tin whisker mitigation strategies</td>
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<td>Design for increased yield for the electronics manufacturing supply chain</td>
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<td>Costing for avionic through life availability (CATA)</td>
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<td>Sustainable ultrasonic electroless and immersion plating process for PV and</td>
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<td>Sustaining electronic industry through managing uncertainty in contract</td>
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<td>Robustness design &amp; health management in power electronics using damage</td>
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<td>Conductive resists for nanofabrication on insulating substrates</td>
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<td>Carbon nanotube composite surfaces for electrical contact interfaces</td>
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<td>Functionalisation of copper nanoparticles to enable metallisation in</td>
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<td>Recycling &amp; sustainable remanufacture of computer PSUs into MPPT solar</td>
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<td>Silver minimisation and replacement in electronics manufacture (AG-Remin)</td>
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<td>Fabrication techniques of carbon-nanotube based PV cells for electronic</td>
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<td>Investigating new research avenues in electronics manufacturing: Naturally</td>
<td>Heriot-Watt, Loughborough</td>
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<td>Broadening integration of printed power sources with electronic systems:</td>
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<td>£14,820</td>
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<td>Rechargeable printed power sources</td>
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IeMRC in Academia

Professor Martin Taylor
Dr Blue Ramsey
Dr Peter Evans
Professor David Harrison
Professor Paul Tucker
Dr Andrew Cobley
Dr Elena Gaura
Dr James Brusely
Dr Larysa Faniyew
Professor Tim Mason
Dr Changhai Wang
Dr David Flynn
Dr Mohammad Taghizadeh
Professor Alan Sangster
Professor Andy Walker
Professor Marc Desmulliez
Dr Stefan Lucyszyn
Professor Andrew Holmes
Dr Mark Miodawrik
Dr Mike Clode
Dr Samjdi Manan
Dr Shahrar Ajaj
Professor Andrew Richardson
Dr Weddong Zhang
Professor David Harvey
Dr Andrew West
Dr David Hutt
Dr Dick Heath
Emma Rosamond
Dr Geoff Wilcox
Dr Mey Goh
Dr Rebecca Higginson
Dr Robert Kay
Dr Robert Seager
Dr William Whittow
David Whalley
Professor Andrew West
Professor Changming Liu
Professor Paul P Conway
Professor Rachel Thomson
Professor Yiannis Vardaxoglou
Professor Tilik Dias
Dr David Selvah
Dr Fredrico Anibal Fernandez
Dr Frank Marken
Dr Linda Newnes
Professor Anthony Mileham
Dr Alex Robinson
Professor Ian A Prece
Professor Richard E Palmer

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Brunel University
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Coventry University
Coventry University
Coventry University
Heriot-Watt University
Heriot-Watt University
Heriot-Watt University
Heriot-Watt University
Imperial College London
King's College London
Lancaster University
Liverpool John Moores University
Loughborough University
Loughborough University
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Loughborough University
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Loughborough University
Loughborough University
Loughborough University
Loughborough University
University of Bath
University of Birmingham
University of Birmingham
University of Birmingham

Aled Jones
Aled Williams
Dr John Graves
Veronica Saez
Bilal Mikhail
Amrash Kasim
Dr Audrey Mandroyan
Dr Gerard Cummins
Dr Robert Kay
Dr Guangbin Doh
Dr Mark Sugden
Kate Cift
Dr Aff PMID Charyya
Dr Mark Ashworth
Dr Guy Banwell
Dr William Whittow

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Loughborough University
Loughborough University
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Loughborough University
Loughborough University
Loughborough University
Loughborough University

PhD Students

John Kemp
Ryan Swee Hoy Yang
Fudi Khushnaw
Hrushikesh Konyakar
Liu Liu
Lina Huentas
Shehu Zakaria
Kaiyun Cui
Yingtai Tian
Deeps Bhattacharya
Robert French
Eshathaksha Kamara

Bangor University
Brunel University
Cambridge University
Copenhey University
Essex University
Liverpool John Moores University
Loughborough University
Loughborough University
Loughborough University
Loughborough University
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Loughborough University
University of Bath
University of Greenwich

Christopher Hughes
Richard Young
Gemma Coughlin
Richard Young
John L. Chen
Ningyang Wang
Bing Maio
Christopher Hill
Zigian Ding
Edward Horsey
Peter Wilson
Roger Landry

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University of Newcastle
University of Nottingham
University of Oxford
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### IeMRC Collaborating Companies

<table>
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<tr>
<th>Company Name</th>
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<td>Renishaw Plc</td>
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<td>Gwent Electronic Materials</td>
<td>RFMD (UK)</td>
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<td>Advanced Therapeutic Materials</td>
<td>Hallmark Cards</td>
<td>Rohm and Haas Electronic Materials</td>
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<td>Aero Engine Controls</td>
<td>Henkel Technologies</td>
<td>Rolls-Royce Plc</td>
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<td>Alstom Grid</td>
<td>Hydrogen Solar</td>
<td>RSL Power and Control</td>
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<td>Amantys Ltd</td>
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<td>Rutherford Appleton Laboratory</td>
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<td>INEX</td>
<td>Sarbe (Signature Industries)</td>
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<td>International Rectifier</td>
<td>Scottish Microelectronics Centre</td>
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<td>Intrinsiq Materials Ltd</td>
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