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Materials: from research to technology and innovation

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Andreas Lendlein and Richard Trask, founding Editors-in-Chief of the new journal Multifunctional Materials, share their vision for publishing high-impact research in this fast-moving field, while Susan Curtis unveils the all-new Physics World site.

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Materials science and technology continues to yield astounding discoveries and inventions, and IOP Publishing (IOP) is proud to have captured many of the most important advances within its expanding materials science portfolio. Extending to more than 20 journals, which together publish more than 7000 articles every year, as well as our award-winning journalism and ebooks programmes, IOP’s materials portfolio provides the community with essential content covering all areas of materials science – from fundamental properties and synthesis through to materials modelling and novel applications that drive technological innovation.

The rapid pace of change in materials research makes it vital that we continue to shape our portfolio to meet the evolving needs of the community. The design and realization of next-generation materials with multifunctional capability is one area of great scientific and technological interest, and our latest journal, Multifunctional Materials, will provide a new outlet that will bridge all aspects of the materials and systems communities involved with multifunctional design. We look forward to publishing the first content in 2018, and on p7 we ask the two founding editors, Andreas Lendlein and Richard Trask, to share their vision for the journal.

We are also excited to be relaunching our award-winning Physics World site with more content, more writers and a greater focus on interdisciplinary research. Materials science will be an important focus area that will benefit from Physics World’s expert coverage of the most exciting scientific breakthroughs and technological innovations, as we explain in more detail on p9.

Once again we’ve had plenty to celebrate in 2017, and this special collection showcases what can only be a small selection of the most exciting research published across IOP’s materials programme in the past year. To find out more, you will find a full rundown of our publishing options on pp34–35.

I take this opportunity to thank all our authors, referees, Board Members and partners for their ongoing support in shaping our materials publishing programme. We hope that you enjoy this collection, and that we have the opportunity to work with you in 2018 and beyond.

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First of all, what is a multifunctional material?
Multifunctional materials are designed to perform multiple functions through prudent combinations of different functional capabilities. Each function contributes a distinct physical or chemical process that deliver system-level improvements beyond the status quo. For example, multifunctional materials can enable “autonomic” structures that can sense, diagnose and respond to external stimuli with minimal external intervention; “adaptive” structures that allow reconfiguration or readjustment of functionality, shape and structural performance on demand; and “self-sustaining” systems with structurally integrated capabilities for power harvesting, storage, and/or transmission.

Why is now a good time to launch a journal focusing on multifunctional materials?
It is now increasingly recognized that multifunctional materials, and their potential for driving technological innovation, represents the future for materials science. Over the past decade, research on this unique class of materials has increased year-on-year, and it is clear that a field that now brings together a truly multidisciplinary community (biology, chemistry, engineering, materials science mechanics and physics) should now be recognized through a dedicated high-quality journal. Informed and shaped by strong support from the community, Multifunctional Materials (MFM) has been designed to serve this emerging area that connects scientists and engineers working across academia and industry.

What do you see as the key characteristics of MFM?
MFM is a multidisciplinary journal with the primary goal of publishing research of the highest quality and impact, with the expectation that papers published in the journal will have a lasting scientific and technological impact. Recognizing the rapid pace of progress and the highly competitive nature of the field, the journal’s peer-review process will guarantee a combination of very strict scientific rigour with the fast-track decision making we that know our authors will demand. Publishing urgent, high-impact work in the most timely manner is the mission.

What steps will the journal be taking to make sure it really captures the very latest cutting-edge research?
From the outset, it will be important for the Editorial Board and editorial staff to engage with the community and identify the latest developments in the field in order to shape the editorial direction of MFM. In addition, the Editorial Board and journal team will oversee rigorous peer review with very high standards for publication. Our expectation is that the rejection rate will be high, although articles that don’t meet the journal’s strict criteria may, after peer review and at the editors’ discretion (and with author approval), be transferred to other relevant journals in IOP Publishing’s portfolio.

How do you plan to maximize the impact of research published in MFM?
Firstly, as part of the launch phase, all articles in the journal will be completely free to read throughout 2018. Additionally, selected articles will be promoted to the community through IOP Publishing’s award-winning journalism service (each article will also have an Altmetric badge to capture the wider online attention we expect content and authors to receive). Authors who wish to supplement their article with a video abstract to broaden the reach and significance of their work to a non-specialist audience will also be able to do so.

What do you think will be the emerging areas that MFM will be targeting in the next five years?
Biologically inspired adaptive materials; the creation of 3D and 4D materials for additive manufacturing (3D/4D printing); the application of functional multimaterials; the design and development of intelligent materials for adaptive change; as well as new types of materials designed and created through current chemistry or synthetic biology. Our commissioning programme already covers off some of these areas, so watch this space!

What is your long-term vision for the journal?
Our aim is to make MFM the first-choice journal for physicists, materials scientists, chemists, engineers, biologists and medical researchers now engaged with multifunctional materials. An essential ingredient will be for MFM to provide a bridge between fundamental science and technological innovation, and we will be working closely with the community to make sure this happens. In short, our vision is for MFM to play a critical part in defining the future direction of research on multifunctional materials.
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Physics World breaks through boundaries

More content, more writers, more coverage, more often. That’s the ambitious plan for the relaunch of Physics World’s digital news service, as Susan Curtis explains.

What is your vision for the relaunch of Physics World’s online news service?
We want to create the number-one source of news and commentary for the global scientific community. Physics World already provides readers in all parts of the world with a compelling mix of daily news, opinion and analysis, and we will be expanding our coverage to explore some of the most exciting innovations emerging from interdisciplinary and applied research. Materials science and technology will be one key area of focus for the new site, as will new approaches in biofabrication and biotechnology.

What makes Physics World so special?
Our mission is to be the most trusted and most respected provider of expert news and commentary for scientists, students and engineers. We have an award-winning team of writers and editors who have the deep scientific knowledge needed to identify the most significant breakthroughs, and to provide readers with an accurate and thought-provoking insight into the latest innovations. By clearly presenting the wider context of the latest developments, we give our readers the information and understanding they need to do their jobs better.

What can Physics World offer to scientists from fields other than physics?
While Physics World emerged from the physics community almost 30 years ago, we know that scientists are increasingly working in interdisciplinary teams to find solutions to the most important global challenges – such as healthcare, energy generation and storage, and sustainable development. Our science communication programme seeks to inform, educate and connect a global scientific readership, and to promote a collective conversation that engages scientific audiences across borders and across disciplines.

Who should read Physics World?
Physics World is primarily written for practising scientists and engineers – whether working in academic research or technology-based industries – as well as university students at both undergraduate and post-graduate level. Our writers and editors take care to convey complex scientific ideas with clarity and flair, which means that scientists working in other fields can quickly grasp the significance of new research results. It also ensures that our coverage can be enjoyed by anyone with an interest in science, including policymakers, funding agencies, and the scientifically invested lay public.

How will Physics World engage with the research community?
Alongside the coverage produced by our professional science journalists, we are reaching out to the scientific community to help us provide our readers with an inside view into the latest research advances. Our key focus here is to offer selected PhD students the chance to boost their science communication skills by working in tandem with our most experienced writers and editors. We’ll provide training and mentorship to students who are eager to improve and refine their scientific writing skills, and we’ll also provide them with a platform to have their work read by thousands of scientists all over the world.

What support will you offer to these student contributors?
We’ll provide some initial training on how to craft compelling news stories about new scientific results. All students will also receive regular feedback from our professional journalists as well as other student contributors, providing ongoing support that will help all participants to develop an excellent skill in scientific writing. All contributors will of course receive full credit for their work, including an author biog and a page listing everything they have written. In addition, each student will receive a welcome pack that will include free digital access to Physics World magazine and our complete portfolio of journals and ebooks.

How can students get involved in this initiative?
Just e-mail me at susan.curtis@iop.org for more information. I look forward to hearing from any graduate students who want to improve their science writing skills, whether they intend to use them for writing future research papers or to develop a career as a science communicator.
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Where technology takes shape
2D materials under the spotlight

A recent special issue of *Journal of Physics D: Applied Physics* explores the science and applications of 2D materials, which exhibit a range of remarkable properties as a result of their atomically thin dimensions. With six guest editors from Korea, India, Australia and the UK, the issue offers an insight into “the cutting-edge issues, unresolved problems, and new results on material properties and device applications” for all types of 2D materials.

The issue includes four topical reviews that examine everything from the prospects for emergent 2D materials beyond graphene to the use of graphene quantum dots in photonic and electronic devices. These are complemented by a number of research articles that describe novel approaches to fabricating all types of 2D materials, and for determining and understanding their optical, electronic and mechanical properties.

While many applications of 2D materials are in their infancy, many articles in the issue explore how the confinement of electrons can be harnessed in electronic and opto-electronic devices. Potential applications explored in the issue include multilayer thin-film transistors, supercapacitors, and highly sensitive photodetectors.

Some articles in this issue:

- **Emergent elemental two-dimensional materials beyond graphene**
  Yuanbo Zhang, Angel Rubio and Guy Le Lay

- **Laser trimming of graphene oxide for functional photonic applications**
  Xiaorui Zheng, Han Lin, Tieshan Yang and Baohua Jia

- **Bolometric detection of terahertz quantum cascade laser radiation with graphene-plasmonic antenna arrays**
  Riccardo Degl’Innocenti et al

2D Materials

**Enzymes produce biocompatible 2D MoS₂**

Molybdenum disulphide (MoS₂) in its 2D form shows promise for diverse applications in biomedical engineering, but it needs a production process that is inexpensive, scalable and environmentally benign. Now, researchers in Spain and Italy have devised an enzyme-based technique that yields a biocompatible product that is well suited to uses in drug delivery, biosensors and tissue engineering. The method is sufficiently general to be applied to graphene and other 2D materials.

MoS₂ is commonly produced using liquid-phase exfoliation, in which MoS₂ powder suspended in water is separated into 2D layers using ultrasound. However, this process generally requires the use of toxic organic solvents or surfactants, which is a problem for biomedical applications.

Enzymes in action

Natural biomolecules bind to 2D flakes of MoS₂, which prevents them from re-aggregating. The team found that the thickness of the flakes was equivalent to a monolayer of MoS₂ coated on each side with AP-LYS, with most of the flakes between 250 and 550 nm across.

The researchers also confirmed that the material remained stable under physiological conditions, with no effect on the morphology or viability of the cells throughout a 48 h incubation. The team now hopes to add specific functionalities to the flakes for applications in biosensors and biophotonics.

**Flexible friend**

Graphene could enable the flexible screens of the future.
Graphene enables colour-shifting electronic skin

Some animals, including chameleons, octopus, and squid, have an impressive ability to change their skin colour for camouflage, temperature control, or communication. Science has attempted to replicate these abilities with artificial skin, but the colour changes are in most cases only visible to the naked eye when the material is put under huge mechanical strain.

Now, however, researchers at Tsinghua University in China have exploited graphene to develop a new type of user-interactive electronic skin that produces a colour change perceptible to the human eye, and that is achieved with a much reduced level of strain. “Graphene, with its high transparency, rapid carrier transport, flexibility and large specific surface area, shows application potential for flexible electronics, including stretchable electrodes, supercapacitors, sensors, and optical devices,” commented senior author Hongwei Zhu.

Reporting their results in the journal 2D Materials, the research team exploited graphene-based flexible electronics to construct a highly sensitive resistive strain sensor along with a stretchable electrochromic device. “We explored the substrate’s effect on the electromechanical behaviour of graphene,” said lead author Tingting Yang.

To obtain good performance with a simple process, the team designed a modulus-gradient structure that allows graphene to be used for both the strain-sensing element and the stretchable electrode of the electrochromic layer. “We found subtle strain – between 0 and 10% – was enough to cause an obvious colour change, and the RGB value of the colour quantified the magnitude of the applied strain,” said Tang.

The results also showed that the mechanical properties of the substrate had a strong effect on the performance of the strain sensing materials. “This is something that has previously been somewhat overlooked, but that we believe should be closely considered in future studies of the electromechanical behaviour of certain functional materials,” concluded Tang.

Graphene composite combines strength with toughness

For a lightweight material, graphene is hard to beat for its strength and toughness. But it remains too expensive and impractical to be used in applications where these properties are most in demand, such as aerospace, automation, infrastructure, and transportation. Graphene oxide (GO) is easier to produce, but is also much weaker than graphene – particularly when made into sheets known as “GO paper”.

Markus Buehler and colleagues at MIT have now addressed this problem by using computer models to design a GO-based composite that combines strength and toughness. “With a lot of inspiration from natural systems, we designed a GO nanocomposite that has better mechanical performance than pristine GO films,” said Francisco Martin-Martinez, one of the MIT researchers.

One key ingredient of the nanocomposite is polydopamine (PDA), an increasingly popular coating material that has been inspired by the adhesion properties of mussels. While other groups have studied PDA composites experimentally, ambiguities over the chemical interactions between PDA and GO made it difficult to create materials with the required properties. Instead, the MIT researchers created molecular models of the system, and then updated the models with data from experiments and materials characterization.

“This represents an advanced predictive tool that makes the production of materials more efficient, reducing the number of experiments required by incorporating atomistic design into the fabrication process,” says Martin-Martinez. The structure of the composite was also inspired by nacre (mother of pearl), which has an outstanding mechanical performance as a result of its brick and mortar configuration. In this case, the GO layers provide the “bricks” with the PDA acting as the “mortar”.

The researchers also tested the effect of humidity on the composite system by introducing water at varying concentrations into their model. They found that adding water to GO-PDA composites widens the spacing between the layers, increasing the strength when adjacent layers were pulled in opposite directions. No such change was observed in pure GO layers.

The researchers acknowledge certain limitations in the model but are still confident in the wider applications of the “bottom-up” design approach. “From the simulations, we can tell which material design yields higher mechanical performance even though we cannot get its actual strength and toughness in the simulations,” concludes Martin-Martinez.

Nano Futures 1 025002
Researchers at Texas Instruments in the US have devised a new technique that could generate large quantities of high-quality hexagonal boron nitride (h-BN), a 2D material that has been tipped for applications ranging from deep-ultraviolet light sources and electronic devices through to protective coatings and solid-state lubricants.

Writing in the journal *2D Materials*, Luigi Colombo and colleagues have also provided new insights into growth mechanism itself, which is essential for scaling up production without compromising on material quality.

Some of the key attributes that researchers want to conserve include h-BN’s high thermal conductivity and excellent insulating properties, as well as its atomically flat crystal surface, chemical inertness and low friction coefficient. Mechanical exfoliation is known to yield high-quality samples, but Colombo and colleagues investigated the characteristics of h-BN grown by chemical vapour deposition, which is a more promising approach for scaling up the quantity produced.

The technique works by exposing metal films to diborane and ammonia at high temperatures before allowing it to cool. Spectroscopic analysis revealed that h-BN films grew by diffusing into the metal film before segregating out, and Colombo and colleagues were able to control the thickness of h-BN by changing the thickness of the metal film substrate.

Probing the optical and electrical properties of the film showed that the resulting h-BN films had “a near theoretical optical bandgap” and “excellent breakdown strength”. The team suggest that the segregation-precipitation method may be a useful approach that can be applied on any arbitrary substrate for producing h-BN films that can be extended to the wafer scale. *2D Mater.* 4 025117

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Quantum materials and technology

Quantum memory is made from doped silicon

Physicists in Australia have shown that quantum information can be stored and retrieved from a single atom of phosphorus embedded in a silicon crystal. Reporting the breakthrough in *Quantum Science and Technology*, Andrea Morello of the University of New South Wales says that this kind of quantum memory could be an important ingredient in silicon-based quantum computers that would be more scalable, compact and easier to mass-produce than devices based on rival technologies.

Morello and colleagues have developed a system that overcomes one of the fundamental obstacles facing quantum computers, which encode data in the form of quantum bits, or qubits. Because it is impossible to copy the state of a qubit or any other quantum object, a quantum memory instead involves transferring a quantum state from one qubit to another, which then erases the state of the first qubit. This requires a two-qubit system composed of a “memory qubit” that is more resilient to external sources of electrical or magnetic interference, and a “processing qubit” that is used to read and write data.

In the latest work, Morello and colleagues have created a natural two-qubit system by doping silicon with atoms of phosphorous. Adding phosphorus to silicon adds an extra positive charge to its crystal lattice, which in turn attracts an extra electron. This effectively creates a hydrogen atom in which the less magnetically sensitive nuclear spin forms the memory qubit, while the electron spin acts as the processing qubit.

In their experiment, Morello and colleagues implanted phosphorus atoms into a 100 × 100 nm² region of a 90 nm-thick layer of enriched silicon. They set the initial state of the phosphorus electron spin using a microwave antenna fabricated on top of the silicon chip. That spin state is then transferred to and from the nucleus using a series of radio-frequency pulses from the same antenna. To read out the value of the electron spin, they created a single electron transistor from aluminium electrodes fabricated on the chip. The transistor is turned on if the electron escapes the phosphorus nucleus, which only happens when it is in its (high-energy) spin-up state.

The researchers found they could transfer the spin state of the phosphorus electron to the nucleus and keep it there for up to 80 ms – “a remarkably long time in the solid state,” says Morello – before transferring it back to the electron and reading it out. Unfortunately, they found that the electron’s final state only matched its initial state around 80% of the time – a fidelity that fell far short of the 99% possible when operating the electron and nuclear qubits separately. They believe this is caused by a shift in the electron’s resonance frequency after they turn on the radio-frequency pulses, and say that they will now work to eliminate this shift. *Quantum Sci. and Technol.* 2 024003

Quantum corrections to conduction in ‘bad’ metals

Condensed matter physicists have their own “standard model” for metals, Landau’s Fermi Liquid theory. FL theory says that the low-energy excitations of a conventional metal are long-lived quasiparticles, and that these quasiparticles propagate many times their own wavelength between scattering events.

This means that electron transport in most metals can be described as a classical gas rather than a quantum system. But some materials exhibit quantum interference effects at low temperatures and on short distance scales, requiring “mesoscopic” corrections to classical conduction. Such mesoscopic corrections are often seen in the magnetoresistance, and include effects such as weak localization and universal conductance fluctuations.

However, there are “bad metals” in which electron scattering is dominated by disorder. One such example is vanadium dioxide, a strongly correlated material with an insulator-to-metal phase transition at about 340 K. The intercalation of atomic hydrogen suppresses that transition, and offers a way to stabilize an unusual metallic state down to low temperatures.

In new research published in *Journal of Physics: Condensed Matter*, Douglas Natelson and colleagues at Rice University and Cornell University in the US have investigated the properties of epitaxial films, single-crystal nanowires, and single-crystal flakes of intercalated vanadium oxide. “We find phenomena that strongly resemble weak localization and universal conductance fluctuations,” says Natelson. “This suggests that quantum coherence effects over longer length scales become important at low temperatures in this system.”

But Natelson points out that there is no self-consistent quantitative model to treat these effects in bad metals. “We hope that this work helps motivate theoretical considerations of quantum transport in bad metals and other systems that appear to deviate from the Fermi Liquid regime,” he concludes. *J. Phys.: Condens. Matter* 29 185601

[Image 212x296 to 281x390]
Quantum materials exhibit a rich landscape of highly degenerate quantum states that are widely regarded to hold vast potential for future applications, ranging from power management and transmission to platforms for quantum computation and novel sensors and electronics. But to realize the promise of these diverse applications, scientists need to identify the fundamental energy scales that control the emergence of such quantum states and their properties.

In new research reported in *Journal of Physics: Condensed Matter*, David Fobes and Marc Janoschek at the Los Alamos National Laboratory (LANL), together with collaborators from the Jülich Centre for Neutron Science (JCMS) in Germany and the University of Tennessee, have investigated the puzzling magnetic structure of the heavy-fermion material CeRhIn₅. In this type of material, the $f$-electrons become localized into so-called $f$-electron orbitals on rare-earth or actinide sites, forming local magnetic moments that interact with conduction electron spins in two possible ways: the so-called Ruderman–Kittel–Kasuya–Yosida (RKKY) interaction that yields long-range magnetic order, and a Kondo interaction that screens the electron moments and results in a non-magnetic state.

“The competition between these two interactions controls the emergence of quantum matter at temperatures near absolute zero,” explains Fobes. “Although the RKKY interaction results in magnetic order, external control parameters, such as pressure, can enhance the Kondo interaction by increasing the overlap of neighbouring valence orbitals, and eventually lead to complete suppression of the magnetic order.”

The strong quantum fluctuations that arise at this magnetic instability, known as a quantum phase transition (QPT), are believed to cause the emergence of quantum matter states and they also alter material properties at much higher temperatures. “This not only showcases the relevance of quantum matter for future applications but also explains why QPTs are one of the most important fundamental issues in solid-state physics,” says Fobes.

In their latest work, Fobes and Janoschek used hot neutrons to precisely measure the ordered magnetic moment in CeRhIn₅, a prototypical $f$-electron material that orders antiferromagnetically. Applying pressure to CeRhIn₅ has previously been found to increase the Kondo interaction and accesses a QPT, around which unconventional superconductivity emerges.

The new experimental results reveal that the ordered magnetic moment is suppressed by 41% compared to the ground state, suggesting that the Kondo interaction has a significant screening effect, even in the magnetically ordered state. “Because there are currently no theories to calculate the magnetic properties in the regime where Kondo and RKKY interaction are of similar size, our work highlights that new theoretical developments are desperately required to understand the emergence of quantum matter,” Fobes concludes.

*J. Phys.: Condens. Matter* 29 17LT01

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**Hybrid devices promise quantum future**

Novel hybrid quantum materials and devices, which combine semiconductors with superconductors, topological insulators or other 2D layered materials or quantum structures, are opening new possibilities in the physics and applications of quantum transport phenomena. Of particular interest is the combination of low-dimensional materials with new electronic device concepts or measuring techniques.

A recent special issue of *Semiconductor Science and Technology* highlights recent advances in the field. The guest editors, Stefano Roddaro from NANO-CNR and Scuola Normale Pisa, Italy, Saskia F Fischer from Humboldt-Universität zu Berlin in Germany, and Koji Ishibashi from RIKEN in Japan, have chosen to focus on four main areas: the fundamental understanding of hybrid quantum structures and devices; quantum transport and new measurement techniques; theoretical modelling; and novel quantum device fabrication and characterization.

Articles in the issue describe both theoretical/computational and experimental techniques. It includes a topical review focusing on the challenge of entanglement distribution in quantum information technologies, as well as a number of original research articles describing novel hybrid approaches.
On the power of tuneable monochromatic light

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| Detector calibration: impart NMI traceable spectral response calibration to your devices. |
| Thin-film deposition monitoring: real-time, automated optical monitor. |
Energy and the environment

Irregular nanopatterns enable micron-thin silicon solar cells

Micron-scale surface textures are known to enhance the absorption and trapping of light in silicon solar cells, and shrinking the features to the nanoscale can improve the optical properties even further. However, the thinnest cells sacrifice electronic performance, which limits their overall energy-conversion efficiency.

Now, the international PhotonVoltaics project has demonstrated a sub-micron-thick, nanotextured silicon film that achieves excellent optical properties without compromising on charge-carrier collection efficiency. Reporting their results in the journal Nano Futures, the researchers expect the new device to have applications not possible with current, much thicker wafer-based cells.

“We strived to enable the development of a new and disruptive solar-cell generation, resulting from the marriage of crystalline-silicon photovoltaics with advanced light-trapping schemes from the field of nanophotonics,” says project leader Valerie Depauw, who is based at imec in Leuven, Belgium. “The main applications of our thin solar cell could be in buildings as windows and skylights, where they will bring more freedom for integration, and possibly lighter and thinner module designs.”

The group started with a micron-thick silicon film, which was imprinted with a nanotexture using reactive ion etching (RIE). The texture was derived from a self-assembled layer of charged polystyrene beads, resulting in an imperfectly periodic pattern of gently sloping, rounded nanocups. Compared to the microscale structures more commonly used for solar cells, the new technique represents a more efficient use of material, with far less silicon discarded during the patterning process.

The method and pattern used by Depauw and colleagues yielded an overall conversion efficiency of 8.6% and an effective thickness of only 830 nm, the highest efficiency yet recorded for such a thin silicon film. Although surfaces of nanowires or nanocolumns have been shown previously to be even more effective absorbers of incident light, the hugely increased surface area leads to more surface recombination losses when used in solar cells. High-quality passivation layers and antireflective coatings are also difficult to apply to such surfaces, lowering the overall efficiency.

The team now plans to squeeze further gains from the cell design and the texturing process. Given discrepancies between the electronic characteristics of patterned and unpatterned silicon films, the researchers propose that the etching procedure itself can affect the performance of the cell. “For dry nanotexturing processes such as RIE, there are four main causes of damage,” explains Depauw. “Wet etching by an alkaline solution avoids such effects and allows higher-quality surface passivation.”

Nano Futures 021001

Journal of Physics D: Applied Physics

Sunlight promises power potential

The increasing threat from global warming is driving research efforts to identify reliable sources of clean energy. Much attention focuses on the Sun, which on its own produces enough renewable energy to satisfy the world’s current power demands. While photovoltaic devices are already in widespread use, researchers are also developing devices for artificial photosynthesis – in other words, the direct conversion of sunlight into storable energy-rich compounds such as hydrogen, hydrocarbons or alcohols.

A recent special issue of Journal of Physics D: Applied Physics highlights recent advances in all aspects of solar fuel production. “This complex energy conversion mechanism involves several processes that need to occur simultaneously and within compatible conditions,” explain guest editors Esther Alarcon-Llado and Miguel Modestino. Such processes include light capture, electronic transport, electrocatalytic fuel generation, and energy collection and storage.

Alarcon-Llado and Modestino point out that novel materials are needed for light absorbers and electrocatalysts, as well as for gas separation and ion transport. Advanced semiconductor engineering is also needed to maximize efficiencies, while innovative design principles will be crucial to realize a fully integrated solar-to-fuel conversion device. Articles in the issue explore all these different aspects of solar-fuel devices and systems.

SOME ARTICLES IN THIS ISSUE

Colloidal nanocrystals for photoelectrochemical and photocatalytic water splitting
Chethana Gadiyar et al
J. Phys. D: Appl. Phys. 50 074006

Degradation in photoelectrochemical devices: review with an illustrative case study
Freddy Nandjou and Sophia Haussener
J. Phys. D: Appl. Phys. 50 124002

Recent developments in complex metal oxide photoelectrodes
Fatwa F. Abdi and Sean P. Berglund
J. Phys. D: Appl. Phys. 50 193002
Cool future beckons for caloric materials

Scientists and engineers have for years been working to reduce the environmental impact of refrigerators, in particular the coolants that can damage the ozone layer. One promising alternative is the use of so-called caloric materials, which respond to an applied electric, magnetic or mechanic field with a reversible temperature change.

This thermal response is generally quite small, but a few materials have now been found to show a “giant” caloric effect in the vicinity of a phase transition. Particularly interesting are first-order transitions with an associated large latent heat, and ferroic and multi-ferroic materials have proved good candidates for displaying giant caloric effects close to the phase transition where the ferroic properties spontaneously emerge.

Journal of Physics D: Applied Physics has now devoted a special issue to giant caloric materials and their potential use as refrigerants. “In recent years, the study of giant caloric materials has received a great deal of attention,” write guest editors Lluís Mahosa and Antoni Planes, of the University of Barcelona in Spain, in their introduction. “There is great hope that they will contribute to the development of an efficient and environmentally friendly technology that is expected to replace current refrigerators.”

Some articles in this issue

- Mixed magnetism in magnetocaloric materials with first-order and second-order magnetoeelastic transitions
  M F J Boeije et al
  J. Phys. D: Appl. Phys. 50 174002

- Elastocaloric cooling of additive manufactured shape memory alloys with large latent heat
  Huilong Hou et al
  J. Phys. D: Appl. Phys. 50 404001

- Elastic-like deformation and elastocaloric effect of a partly ordered iron-platinum alloy exhibiting a weak first-order martensitic transformation
  Takashi Fukuda and Tomoyuki Kakeshita
  J. Phys. D: Appl. Phys. 50 404003
Scientists in South Korea have come up with a new 3D printing strategy for engineered human skin that they claim could be 50 times cheaper than current methods. Reporting their results in the journal *Biofabrication*, the team from Pohang University of Science and Technology have shown that their new printing technique can generate fully functional human skin in a single-step process.

“Although several approaches have been explored for developing biomimetic human skin models, the present skin models are still based on multistep production methods using polydimethylsiloxane (PDMS) chips and commercial cell culture inserts,” says lead author Dong-Woo Cho. “These could be limited in making a versatile design that facilitates the development of various functional human skin models. In this regard, the 3D cell-printing technique could establish a new era for advanced skin models.”

The researchers developed a hybrid 3D cell-printing system that allows both the extrusion and inkjet modules to be used on the printer at the same time. They used the extrusion-dispensing module to engineer a collagen-based material with a membrane made of polycaprolactone (PCL), a biodegradable polyester that prevents collagen’s contraction during tissue maturation. The inkjet-based dispensing module was used to uniformly distribute keratinocytes – the predominant cell type in the outermost layer of the skin – onto the engineered skin.

This process allowed the team to build a supportive 3D construct in a single process, enabling the maturation of the skin model without the need for commercial cell culture inserts. The skin model also displayed good biological characteristics, including a stabilized/fibroblast-stretched dermis, and stratified epidermis layers after 14 days.

“Our new method is around 50 times cheaper than alternative methods, and requires 10 times less base material,” says Cho. “We hope that this new single-step process could provide an attractive and useful platform for engineering fully functional human skin models.”

*Biofabrication* 9 025034
Scaffold breakthrough could banish implant infections

Researchers in Ireland have developed a new type of implant scaffold that has already proven effective against two types of major problem bacteria. Dimitrios Zeugolis and colleagues at National University of Ireland Galway created stabilized collagen scaffolds that could be loaded with specific antibiotics, providing localized drug treatment that prevents the formation of bacteria such as E. coli and Staphylococcus epidermidis.

“Implant infections remain a major healthcare problem,” comments Zeugolis. “Although localized drug treatment via an implanted scaffold has shown promise, the ideal scaffold cross-linking to initially withstand the aggressive infection environment and drug to fight against infection have not, until now, been found.”

Reporting their results in the journal Biomedical Materials, Zeugolis and his team first developed a collagen scaffold, and stabilized it with a 0.625% concentration of hexamethylene diisocyanate (HDI). They then tested the scaffolds with variable concentrations of the antibiotics Cefaclor and Ranalexin.

The researchers found that both drugs showed similar loading efficiency, release profile and cytocompatibility. However, only collagen scaffolds loaded with 100 µg/ml of Cefaclor showed adequate antibacterial properties against both E. coli and Staphylococcus epidermidis. “Our cross-linked collagen scaffold marks an important step forward against an issue that is both a major health problem and a severe economic burden to healthcare systems internationally,” concludes Zeugolis.

Biomed. Mater. 12 035013

Better bioscience
Lab tests on engineered tissue could reduce the need for animal testing.

Biofabrication has exploded as a very dynamic field over the past 20 years and will soon produce many technologies for industry to exploit and improve product development. As the review suggests, opening channels of communications between bioengineers and chemical developers will be key to stepping further away from animal research.

About the author: Gregor Skeldon is a PhD student contributor to medicalphysicsweb, who studies at Heriot Watt University in Edinburgh.

Biofabrication 9 033001
Plasma-treated molecules expand the antibiotic arsenal

New research has shown how the natural chemical defences used by plants could be deployed more effectively in the fight against bacterial infection. These naturally occurring molecules are usually too weak to be used for medical treatment, but a collaboration between scientists in Australia, Singapore and the US has now devised a simple single-step process to boost the potency of such plant secondary metabolites (PSMs).

Reporting their result in Nano Futures, the team describes how treating PSMs with plasma makes them more effective against Staphylococcus aureus, a common cause of infections in humans. They hope that the method could greatly extend the range of antibiotic substances available to clinicians, and help stem the rise of drug-resistant bacteria.

Previous work has shown that PSMs can be made more effective through exposure to plasma, since this generates reactive species such as hydroxyl radicals, ozone and hydrogen peroxide. “Our group recently showed that plasma treatment of amino acids changes their structure,” team member Kateryna Bazaka told nanotechweb.org. “It gave us the idea that direct treatment of biologically-active molecules, such as PSMs, may also induce some beneficial changes in these molecules, enhancing their activity without using chemicals or heat-based treatment.”

To test their technique, the team exposed solutions of two different PSMs – terpinene-4-ol and γ-terpinene – to an argon plasma at ambient pressure. Terpinene-4-ol, familiar for its presence in tea tree oil, is known to have an antibacterial effect in its pristine form, while unmodified γ-terpinene only has limited efficacy against S. aureus.

When the plasma-potentiated solutions were applied to S. aureus as a free-floating suspension and as a biofilm, the researchers found that the modified PSMs significantly reduced both the biofilm thickness and numbers of suspended colony-forming cells. Although terpinene-4-ol was still the more potent chemical after activation, even the otherwise ineffective γ-terpinene caused significant changes to the biofilms and suspended bacteria.

Bazaka and her collaborators expect plasma treatment to be just as effective for other PSMs. What’s more, says Bazaka, “depending on the chemistry of the original molecule, the activity of the product will be different, which is an excellent opportunity to optimize against a specific pathogen.”

The reactive oxygenated species generated by the plasma persist for up to 24 hours, and the simplicity of the approach and the affordability of the equipment make plasma activation a widely accessible technique. “In fact,” says Bazaka, “the device used in this study is certified in Europe to be used by medical and veterinary practitioners for wound treatment. It can be easily scaled up.”

Molecular movements in biomembranes

Researchers working at the interface between biophysics and cell biology are focusing much of their attention on cell membranes, since important processes such as adhesion, signalling and recognition exploit the properties of the two-dimensional membrane matrix. In fact, about one third of the eukaryotic genome encodes proteins found in cell membranes, suggesting that the membrane is a crucial site for protein–protein interactions.

A recent special issue of Journal of Physics D: Applied Physics attempts to capture the latest experimental and theoretical research into the movements of molecules in biomembranes. Guest editors Eugene Petrov of the Max Planck Institute of Biochemistry in Martinsried, Germany, and Gerhard Schütz of TU Wien in Austria, have brought together review articles and original studies of both model membrane systems and live cell membranes.

“Recent research has revealed that there is a variety of ingredients that modulate molecular movements in the membrane,” write Petrov and Schütz in their introduction. “We believe that this special issue provides a timely overview over the current concepts and questions about the movements of membrane constituents, and we wish you an exciting and entertaining read.”
A longer-lasting heart valve

Diseased heart valves can sometimes be replaced with biological substitutes from donors, but clinicians must usually rely on bioprosthetic valves based on tissues taken from animals. Researchers at the University of Padua have now shown that a new decellularization technique can prevent the factors that cause these replacement heart valves to deteriorate in the body, and even to be rejected after initial implantation.

Bioprosthetic heart valves based on animal tissue, such as bovine pericardium, typically show structural deterioration after 10–15 years. The problem is thought to lie with the use of crosslinking agents such as glutaraldehyde (GA) in the treatment of animal pericardium before use, making it imperative to develop GA-free biological materials.

The Italian research team has tested whether a new decellularization method called TRITDOC could solve the problem. Reporting their results in Biomedical Materials, they find that TRITDOC can eliminate the alpha-Gal xenoantigen, which is the main factor responsible for hyperacute rejection after transplantation.

“The TRITDOC procedure does not affect the biological, mechanical and functional characteristics of the treated tissue,” explains first author Paola Aguiari. “It ensures cyto/immunological properties superior or comparable to those of pericardial patches currently used for manufacturing FDA-approved bioprosthetic heart valves.”

After applying the TRITDOC protocol to bovine pericardium patches, Aguiari and colleagues tested the efficacy of TRITDOC in eliminating alphaGal. Native bovine pericardium contained $26 \times 10^{10}$ alphaGal epitopes per 10 mg of tissue, while no reactive alphaGal epitope was detected in TBP. This contrasts with the GA treatment applied to commercial bioprostheses, which does not completely mask the presence of alphaGal.

The researchers also confirmed that TBP provides an effective scaffold for cell adhesion and colonization, based on tests with human macrophage cells. Comparing TBP with two commercial bioprostheses, as well as GA-treated TBP, they found that cell adhesion 72 hours after seeding was significantly higher than on the other substrates.

All samples showed a significant increase in cytotoxicity over time, as measured by the presence of LDH, an enzyme leaked from damaged cells. GA-treated TBP was also found to reduce the activation of the complement system – a key event in the immune response to biomaterial implantation – which suggests that TBP could provide a promising candidate material for production of prosthetic heart valves.

“The aim of this study was to evaluate the compatibility of TBP with the immune system, and its potential to provide a suitable scaffold for cell adhesion/infiltration and proliferation without any cytotoxic effect,” said Aguiari. “The natural extension is aimed at testing the in vivo performances of the cellular scaffold. Currently, the biomaterial is employed in the manufacture of transcatheter valves, whose hydrodynamic behaviour and long-term tendency to calcific degeneration must be assessed.”

Biomed. Mater. 11 015021
Manufacturing and materials processing

Roadmap points to plasma future

Leading experts in low-temperature plasma science and technology have collaborated on a major new work that provides fresh insight into the research needs and opportunities in this technologically important research field. The 2017 Plasma Roadmap, published in *Journal of Physics D: Applied Physics*, synthesizes the perspectives from 38 scientists and engineers in 19 sub-disciplines, ranging from plasma theory and modelling through to novel fabrication techniques and applications in key industry sectors.

“The field of low-temperature plasmas is exceptionally interdisciplinary with grand-challenge level scientific questions that have a dynamic range that is perhaps greater than any other field of physical science,” write the editors, Peter J Bruggeman, Uwe Czarnetzki and Mark J Kushner, in their introduction. “While the field is extremely diverse in its applications and related science, common to all subfields is the requirement to control and understand non-equilibrium plasma kinetics and the interactions of plasmas with matter.”

The new roadmap represents a comprehensive update of a previous version published in 2012. The format of the roadmap remains the same, although each section is now written by two authors to stimulate discussions within each area. The topics tackled in the 2017 roadmap have also been updated to reflect ongoing innovation in the field, while several sections have been added to deal with more fundamental plasma science, including the important topics of transport in plasmas and plasma theory.

Despite the technological success of low-temperature plasmas, the editors point out that fewer research groups are focusing on these more fundamental studies. “There are many root causes for this trend, one being that funding is increasingly being focused on applications,” they caution. “If this trend continues unabated, the health of the low-temperature plasma field is at risk. As the field moves forward and the technological advances emerging from the field continue to provide societal benefit, we should also continue to make investments in the fundamental topics of plasma science that underpin this technological advancement.”

They also underline the importance of training young scientists and engineers in the fundamentals of plasma science. “The field of low-temperature plasmas depends on nurturing and supporting new generations of scientists and engineers involved in plasma science, modelling and diagnostics,” they write. “The training of this next generation of scientists and engineers in the fundamentals of plasma science becomes an increasingly challenging task particularly in view of the growing interdisciplinary nature of the field.”

**Nano Futures**

**Nanopatterning achieves structural colour at low cost**

Paper and pigments used to record text and images can degrade in decades, while long-lifetime forms of information storage, such as Blu-ray discs, can be made obsolete by technological changes. Now, Hao Jiang and colleagues at Simon Fraser University in Burnaby, Canada, have developed a flexible, low-cost technique to print structural colour in a long-lived epoxy. The method can be used to make eye-readable records that should last for centuries.

The Canadian group, led by Bozena Kaminska, devised an optical technique called NETT (which stands for nanoimprint, exposure, and thermal treatment). Described in the journal *Nano Futures*, the process starts with a quartz stamp patterned with a periodic arrangement of sub-micron-sized, cone-shaped pits. Three configurations of pits are repeated in bands across the surface of the stamp, corresponding to red, green and blue for a given set of viewing and incident angles.

This master stamp is then pressed into a photoresist layer to create a repeating pattern of the three nanocone types. Regions of different colours can be created by patterning the photoresist layer with a UV laser and then curing the surface in a two-step baking process. This preserves the structure of the nanocones in the irradiated areas, while the unexposed nanocones merge into a flat background and become black or inactive pixels.

The NETT procedure has so far achieved an image resolution of approximately 338 pixels per inch, which is close to the resolution limit of the human eye. At the moment, however, colour fidelity is preserved only for a viewing angle of about 5°, an issue that the team plan to address in future research.

“The next phase of development will use plasmonic colours, which are angle-independent, so that the viewing angle will be very wide, at least up to 60°,” says Jiang. Plasmonic colours require the fabrication of metallic nanoholes and nanodisks, for which the NETT technique can also be applied.
Nanotechnology

Electrolytic cleaning tackles graphene residues

The pesky residues left behind when transferring graphene grown by chemical vapour deposition (CVD) have remained a challenge for this potentially scalable approach to high-quality graphene production. Now, in new work reported in Nanotechnology, researchers at West Virginia University in the US have demonstrated a simple electrolytic cleaning method for removing these PMMA contaminants.

Thermal annealing is widely used to remove PMMA once it has been used to transfer graphene layers from its growth substrate, but the residues have been linked to p-doping and reduced carrier mobility. In their study, Jianbo Sun, Harry O Finklea and Yuxin Liu, used Raman spectroscopy to reveal that the residues after thermal annealing were conjugated unsaturated carbon systems left behind as the PMMA was heated off.

They then showed that by using a cathodic electrolytic cell, similar to methods for cleaning rust from iron and other conducting surfaces. Gas bubbles released during the electrolysis were found to strip the residues from the graphene surface, and testing the graphene in simple field-effect transistors demonstrated a significant improvement in its electronic properties.

Nanotechnology 28 125703

Flexible and Printed Electronics

Smart paper benefits from low-cost printing

Using paper as a substrate for printed electronics has many obvious advantages: it is cheap, flexible and biodegradable, and it can be disposed of easily through composting or incineration. Many paper-based products could also benefit from added functionality or intelligence, which has motivated research into “throw-away” paper electronics for applications such as signage, energy harvesting and storage, and sensors for food spoilage and bioanalytics.

A recent focus issue of the journal Flexible and Printed Electronics reveals how researchers are attempting to exploit paper as a substrate for electronic devices. The three guest editors, Ronald Osterbacka from Åbo Akademi University in Finland, Elvira Fortunato from the Universidade Nova de Lisboa, Portugal, and Andrew J Steckl from the University of Cincinnati in the USA, point out that “the devices need to include all types of electronic components for self-powered operation, as well as active and passive circuit components, transistors and logic circuits, input and output elements, and so on.”

Equally important are effective production technologies, including printing processes that enable low-cost and fast-throughput patterning, as well as fabrication techniques designed specifically for paper-based substrates. As an example, researchers in Sweden describe a pilot-scale manufacturing process for functional composite papers that incorporate zinc oxide nanowhiskers to provide photosensing properties.

The resulting photosensors offer high sensitivity over a wide range of irradiances, and also show short response times and long-term stability. “To the best of our knowledge, this is the first example of pilot paper machine production of an optoelectronic paper,” the authors write in their abstract. “This demonstrates the potential for large-scale paper manufacturing of active smart paper from low-cost industrial bulk materials.”

SOME ARTICLES IN THIS ISSUE

Photoconductive zinc oxide composite paper by pilot paper machine manufacturing

Mats Sandberg et al

Non-volatile aluminum oxide resistive memory devices on a wrapping paper substrate

Ji Jong Jang et al

Printable cellulose-based electroconductive composites for sensing elements in paper electronics

R Barras et al

Nano Futures

Block copolymers spiral under control

The simplicity of “bottom up” self-assembly has long vied with the extreme control of more painstaking “top down” lithography techniques for fabricating structures at the nanoscale. Now, however, an international research team from the US, Singapore and Korea has shown how templated block copolymers can deliver an impressive level of control over the self-assembly process.

Reporting their results in the journal Nano Futures, the researchers used templated block copolymers to create reproducible arrays of flat spirals, where even the chirality of the structures can be controlled by design. The research team, led by Caroline Ross from the Massachusetts Institute of Technology, also modelled the self-assembly process to predict the geometries resulting from different parameters.

Block copolymers are long molecules in which a strand of one polymer is joined with one or more other polymers. These two polymers form different domains within the material, from which microstructures emerge: an even ratio of two polymer types can lead to interlacing lamellae structures, while a less balanced ratio can generate spheres or cylinders within a matrix of the dominant polymer.

Simple templates can then be used to impose long-range order on the formation of these structures. As an example, doughnuts and “bulls-eye” structures of concentric rings can be formed by templating circular pits. “All we have to do is make the pits and nature takes care of the rest,” says Ross. “But the emphasis in this paper was to make spirals and to do this we needed to break the symmetry of the circular pit.”

The researchers introduced notches on the edge of the pit to force a spiral to form. An asymmetric notch could also be used to control the direction of the spiral, while a deeper notch produced double spirals. The results could ultimately simplify the fabrication of complex structures for photonics and electronics, but this work was not motivated by a specific application. “We were more interested in the science behind the self-assembly,” explains Ross.

Nano Futures 1 015001
Coming soon

A new-look Physics World website
More content, more writers, more coverage. Covering a broader range of science news than ever before, the redesigned Physics World website will have its own dedicated materials science channel to bring you the latest breakthroughs and news.

physicsworld.com
Advances in silicon transistor technology have sustained Moore’s Law for decades, but the physical limits of silicon now require alternative transistor materials for progress to continue. Researchers at the University of Texas at San Antonio in the US are now investigating how new tricks might be coaxed from nanosctructured silicon–germanium (SiGe).

SiGe has already been adopted in mixed-signal and analogue circuits due to its narrower band gap and shorter response time than silicon. Furthermore, says lead researcher Gregory Guisbiers: “SiGe can be easily integrated into the existent Si technology because SiGe is totally miscible with Si all over its composition range. This allows the mismatch stress with the silicon wafer to be controlled by tuning the composition of the alloy.”

But device engineers need a better understanding of how the alloy behaves at the nanoscale. Writing in *Nanotechnology*, Guisbiers and his PhD student Brandon Bonham describe how they used the principles of nanothermodynamics to predict how particle size and shape affect SiGe’s thermal and optical properties, as well as the miscible–immiscible phase transition.

One finding from the study was expected: moving from the bulk material to a nanoparticle causes the phase diagram to shift downwards, and the smaller the particle, the greater the effect. One additional consequence is that smaller particles of SiGe have a wider band gap for a given composition.

Less expected was the discovery that the magnitude of the size effect was controlled strongly by the shape of the nanoparticle, and in particular by the number of facets. Cubic and tetrahedral nanoparticles showed a much greater downward shift in their phase diagrams as particle size decreased – and a correspondingly large increase in their band gap.

Yet more surprising was that the miscible–immiscible phase transition stayed largely constant across all nanoparticle shapes and sizes, barely differing from that of the bulk material. “Consequently,” says Guisbiers, “the region where the SiGe (randomly mixed) can be synthesized is reduced at the nanoscale compared to the bulk scale. People may think that the phase diagram was just going to be shifted downward to a lower temperature in the same manner for all the phase transitions, but this is not the case.”

In the near term, Guisbiers and Bonham’s new results will help researchers synthesize SiGe nanoparticles with sizes, shapes and compositions relevant to their experiments. Eventually, transistors consisting of single SiGe nanoparticles with specially tuned electrical properties may allow Moore’s Law to continue to hold, even when the possibilities of pure-silicon have been exhausted.

**Nanoparticle shape controls properties**

Recent experimental work has promoted germanane from great in theory to truly promising in practice. Synthesized for the first time only a few years ago, investigations on the two-dimensional material have revealed excellent charge transport properties and a useful electronic bandgap. Now, researchers at the University of Groningen in the Netherlands and the University of Ioannina in Greece have fabricated the first field-effect transistor to be made from germanane, further highlighting its promising electronic and optoelectronic properties.

Reporting their results in the journal *2D Materials*, Madhushankar Bettadahalli Nandishiah and his team explain how they isolated germanane using a similar approach to that used for its first reported synthesis, through the topochemical deintercalation of CaGe2. Various characterization techniques confirmed that the sample was indeed germanane – a hexagonal lattice of germanium with hydrogen covalently bonded to each germanium atom. The team then cleaved the resulting flakes to thicknesses ranging from 15 to 90 nm, and placed them on top of a 300 nm Si/SiO2 substrate. Standard electron-beam lithography was then used to fabricate Ti/Au contacts to the device.

Further electronic studies showed good charge transport in all doped regions of the device, with carrier mobilities of up to 150 cm2/Vs at room temperature. Tests also confirmed that the FET shows ambipolar transport properties with enhanced conductivity under illumination at the bandgap wavelength of 650 nm.

**Germanane promise**

The first field-effect transistor to be made from the emergent 2D material.

**Germanane FET offers promise for optoelectronics**

*2D Materials*
Soft lithography yields big results for plasmonic filters

While colours derived from photonic interactions with nanostructures are more stable than the chemical colour sources in polymers and dyes, nanostructure arrays are prohibitively expensive to produce over large areas. Now, however, a team of German researchers has devised a soft lithography approach that increases the area of previous nanophotonic arrays by a factor of 23.

“This might open the way for real applications,” says Max Rumler, a PhD student working with supervisor Lothar Frey at the University of Erlangen-Nuremberg and the Fraunhofer Institute for Integrated Systems and Device Technology. The new approach filters light colours using “plasmons”, the wavelength-dependent quantized collective responses of electrons in metal nanostructures. “The effect is well known but lots of publications only deal with square millimetres or a centimetre at the most, so I thought I would try and increase the area for these,” Rumler adds.

The researchers optimized their soft lithography approach to produce aluminium colour filters with an active area of 145 cm². A master stamp made from silicon was used to imprint the array into a polymer resist, which is then etched to transfer the array structure onto the aluminium surface. They also tailored the thickness of the metal array and coating for improved performance, and identified the plasmon modes using frequency-domain numerical simulations.

Structures produced by this kind of soft imprinting approach can be prone to defects, but Rumler suggests that photonics applications such as camera filters can be quite tolerant to small imperfections. The refractive index sensitivity of the plasmonic colour filters could also be applied to detect bacteria and other substances in biotech sensors.

Future work will aim to calculate the defect density and ways of controlling and reducing it. “Increased contact area usually means larger separation forces so I would suggest looking into this as the main source of defects, which then limits the lifetime of the mould,” says Rumler.

The peculiar attributes of 2D transition metal dichalcogenides (TMDs) are increasingly being exploited to produce microelectronic devices. To meet the needs of specific applications, the properties of these materials – such as the band gap, photosresponse, or charge carrier mobility – can be tuned by using different numbers of layers, applying mechanical strain, or by introducing dopants.

Using MoS₂, one of the more commonly studied 2D TMDs, Ze Xiang Shen and colleagues at Nanyang Technological University, Singapore, and collaborators at Oak Ridge National Laboratory in the US and CINTRA CNRS in Singapore, have achieved the same tunable response by stacking layers of MoS₂ with alternating orientations. The degree of rotation between the layers determines whether certain sites within the structure are vacant or occupied by an atom.

Reporting the work in 2D Materials, the team used chemical vapour deposition (CVD) to create junctions formed by the interfaces between differently stacked MoS₂ bilayers (AA and AB). The group also used the same technique to combine a monolayer (1L) with each type of bilayer arrangement, resulting in either AA-1L or AB-1L trilayers.

Although the MoS₂ monolayer initially deposited has a single crystal structure throughout, the layers laid down on top contain distinct phase domains. By carefully manipulating the deposition process, Xia and colleagues were able to produce flower-shaped structures in which the AA-1L, AB-1L and AA-AB junctions were all present.

The group then fabricated field-effect transistors to test the electronic and optoelectronic properties of the different junction types. All three junctions showed current rectification behaviour, though this was weaker in the AA-AB configuration. Shen’s team also found an asymmetric photosresponse in every type of junction, with negligible photocurrent at zero bias, and a greater photocurrent at forward bias.

“These MoS₂-based homojunctions are intrinsically formed by one-step chemical CVD growth without any heavy doping or mechanical transfer strategies, which guarantees a chemically homogeneous character and strong coupling among the layers,” explains team member Xia. “Our finding demonstrates the promise of using stacking-modulated 2D materials for future electronics and optoelectronics.”

Nano Futures 1 015002

2D Materials

Stacked layers offer tunable electronics

The electronic and optical properties of few-layer molybdenum disulphide (MoS₂) have been shown to change depending on how the component layers are arranged. Researchers in Singapore and the US have used this stacking-modulated effect to fabricate a pure-MoS₂ structure that demonstrates current rectification and an asymmetric photosresponse. They believe the technique could be used to produce future generations of single-material electronic and optoelectronic devices.

The peculiar attributes of 2D transition metal dichalcogenides (TMDs) are increasingly being exploited to produce microelectronic devices. To meet the needs of specific applications, the properties of these materials – such as the band gap, photosresponse, or charge carrier mobility – can be tuned by using different numbers of layers, applying mechanical strain, or by introducing dopants.

Using MoS₂, one of the more commonly studied 2D TMDs, Ze Xiang Shen and colleagues at Nanyang Technological University, Singapore, and collaborators at Oak Ridge National Laboratory in the US and CINTRA CNRS in Singapore, have achieved the same tunable response by stacking layers of MoS₂ with alternating orientations. The degree of rotation between the layers determines whether certain sites within the structure are vacant or occupied by an atom.

Reporting the work in 2D Materials, the team used chemical vapour deposition (CVD) to create junctions formed by the interfaces between differently stacked MoS₂ bilayers (AA and AB). The group also used the same technique to combine a monolayer (1L) with each type of bilayer arrangement, resulting in either AA-1L or AB-1L trilayers.

Although the MoS₂ monolayer initially deposited has a single crystal structure throughout, the layers laid down on top contain distinct phase domains. By carefully manipulating the deposition process, Xia and colleagues were able to produce flower-shaped structures in which the AA-1L, AB-1L and AA-AB junctions were all present.

The group then fabricated field-effect transistors to test the electronic and optoelectronic properties of the different junction types. All three junctions showed current rectification behaviour, though this was weaker in the AA-AB configuration. Shen’s team also found an asymmetric photosresponse in every type of junction, with negligible photocurrent at zero bias, and a greater photocurrent at forward bias.

“These MoS₂-based homojunctions are intrinsically formed by one-step chemical CVD growth without any heavy doping or mechanical transfer strategies, which guarantees a chemically homogeneous character and strong coupling among the layers,” explains team member Xia. “Our finding demonstrates the promise of using stacking-modulated 2D materials for future electronics and optoelectronics.”

2D Mater. 4 035011
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### Hybrid pixel detectors – what are they and what can I do with them?

Detectors have long been a limiting factor in electron microscopy experiments, but we have now entered an exciting phase with new detector technology coming into play. In recent years, one of the most dramatic advances in structural biology has been in the deployment of backthinned CMOS direct detectors to attain near-atomic-resolution molecular structures with electron cryo-microscopy (cryo-EM). Here we discuss the hybrid pixel detector (HPD) technology pioneered by the high-energy physics community at CERN, and its relevance to the materials science community.

#### Direct detection
HPDs consist of a thick, highly resistive pixelated semiconductor sensor bonded to an adjacent readout application-specific integrated circuit (ASIC) that processes the signal. Incident electrons generate charge in the sensor, which diffuses under an applied bias to the CMOS circuitry of the individual pixels via an array of micro-bump bonds. Specifically, we discuss the MERLIN hybrid pixel detector consisting of a Medipix3 chip developed at CERN, and readout electronics developed at Diamond Light Source. In the Medipix3 chip, each pixel contains more than 1100 transistors within its 55 micrometre pitch, enabling on-chip counting of incident electrons and enhanced operation modes such as the Charge Summing Mode. This detector is now commercially available in electron-microscopy-suitable housing from Quantum Detectors Ltd.

#### Noise-free detection and single-electron counting
The MERLIN detector is a particle-counting device, capable of discriminating single electron hits from the electronic noise present in any system. Each pixel of the readout ASIC is comprised of an amplifier – which amplifies the electric charge pulse generated in the sensor by an incoming particle, a discriminator – that generates a digital pulse signal if the incoming electron flux exceeds an adjustable predefined threshold, and a digital counter – which counts the number of generated digital pulses. This digital detection and storage scheme achieves noiseless determination and readout of the number of detected electrons per pixel.

#### Zero dead time
The Medipix3 chip has an architecture that implements two readout counters per pixel, allowing every pixel to record electron hits through one counter while the information on the second is being transferred. This eliminates the requirement for a non-active detector frame store area and provides a continuous read/write acquisition mode with zero detector dead time.

#### Rapid readout
MERLIN provides high versatility with a variety of intrinsically fast and large dynamic range acquisition options, namely: 14,400 fps@1 bit depth, 2,400 fps@6 bit depth, 1,200 fps@12 bit and 600 fps@24 bit depth. These readout modes are unbinned and therefore imply no reduction of pixel resolution or field of view. Since MERLIN adds zero noise, this allows a signal to noise ratio (SNR) as high as 16.7 million:1.

#### Exceptional dynamic range
The characteristic times of the shaping and amplification of the pixel readout circuitry limits the electron count rate to 10 million electrons per square millimetre. If the incoming electron flux is below this limit, an operational mode using a 24 bit counter allows an impressive 16.7 M counts per pixel.

#### Improved MTF with charge summing mode
When an electron strikes near the edge of a pixel, the resulting charge may leak into neighbouring pixels, thus reducing the modulation transfer function (MTF). MERLIN has a unique capability where information is shared between adjoining clusters of four pixels, in what is known as the Charge Summing Mode. When charge spread occurs over the four adjoining pixels, MERLIN recognizes that this information belongs to one event on one pixel rather than up to four weaker events on four pixels. By reconstructing the event using the diffused charge data, MERLIN increases the resolution and ensures an accurate reading of the event, giving a much improved MTF without degradation in detective quantum efficiency.

#### Radiation hard
With a design originating in particle tracking in high-energy physics, the Medipix3 chip is extremely robust, able to withstand large doses of radiation without impact to its performance. An active detector thickness of up to 500 µm absorbs incident electrons with energies up to 300 keV and ensures no radiation exposure is received by the counting circuitry. Extended exposure tests of several hours performed with 300 keV electrons and tens of nA beam currents have shown no adverse impact upon on MERLIN sensor performance. Theoretically, there is no identifiable mechanism by which MERLIN can be permanently damaged by electron beam exposure for energies of 300 keV and below.

#### Experimental flexibility
The frame rates stated do not prevent the MERLIN detector from acquiring data in narrower time windows. In particular, the system is able to count electron hits in periods of less than a few hundreds of nanoseconds. The MERLIN detector can also be “gated” via an external trigger, providing counting during a temporal window of the user’s choice. These extremely short counting periods and external triggering can be advantageous for applications such as 4D STEM, electron diffraction, pump-probe and laser triggered experiments.

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Magnetism and spin

Spin current seen in topological insulator

Emerging research in spintronics looks set to underpin a new revolution in electronic devices and computing. In a recent letter in Journal of Physics: Condensed Matter, Davide Bugini and his team at Politecnico di Milano investigate the properties of the topological insulator Bi$_2$Se$_3$, and reveal promising results for opto-spintronic devices.

“Faster and more power-efficient devices are imperative, but our technology is currently approaching the fundamental scaling limit,” commented Bugini. “A breakthrough is needed for the next-generation of computational and storage devices.”

Bugini explains how scientists are trying to add an additional degree of freedom to the electronic charge – the “information carrier” in today’s electronics devices – by exploiting electronic spin, a purely quantum property. In this move towards spintronics, much attention has focused on topological insulators, which behave as insulators but have a spin-polarized metallic surface that allows a spin current to flow.

However, complete control of these spin currents has proved difficult to achieve. Ultrashort light pulses seem to offer the best option, since circularly polarized light have been found to control spins with extremely fast response times.

Bugini and his team have now reported the first experimental evidence of a direct coupling between circularly-polarized ultrashort light pulses and the spin-polarized population of unoccupied surface states of Bi$_2$Se$_3$. Using time- and angle-resolved photoemission spectroscopy, the researchers were able to track the movement of flow spin-polarized electrons in momentum space – in other words, a light-induced spin current.

“We provide evidence of a transient spin-current in topological insulators triggered only by direct optical coupling to an empty spin-polarized topological state,” said Bugini. “Our fascinating results are just a preview of the next-generation ultrafast opto-spintronic devices that promise to revolutionize our electronic technology.”

Journal of Physics D: Applied Physics

Magnonics promises faster processing speeds

Electronic devices may have enabled the information revolution, but our continuing demand for ever faster processing speeds is driving research into alternative architectures. This has stimulated researchers to investigate the potential of magnons – quantized spin waves in magnetic materials – as a new form of information carrier. The wavelengths of these spin waves can be as small as a few nanometres, orders of magnitude smaller than electromagnetic waves, while their transport properties can be reconfigured on a sub-nanosecond timescale.

A recent special issue of Journal of Physics D: Applied Physics explores this emerging research field, now known as magnonics. “Recent developments in spintronics as well as photonics show the potential of magnons to be converted into spin currents, and vice versa, including the direct and inverse spin Hall effects. “On the other side, the ultrafast demagnetization and all-optical switching via ultrafast laser sources promise a wealth of possible interactions between magnons and photons,” they write.
New horizons for modern magnetism

Leading experts in magnetism have combined their knowledge and expertise to produce a forward-looking roadmap for novel magnetic materials and devices, as well as their potential applications. Published in Journal of Physics D: Applied Physics, the roadmap offers an important reference point for emerging research directions in modern magnetism.

The roadmap consists of 14 sections, each written by an expert in the field, covering key topics in magnetic materials; the underlying physics of magnetic phenomena; and device development for applications in non-volatile memories, spintronics, energy, and biomedicine. “The 2017 Magnetism Roadmap provides a framework that will enable the reader to judge where each subject and magnetism research field stands today, and which directions it might take in the foreseeable future,” write the authors in their introduction.

The 2017 edition provides a comprehensive update of an earlier roadmap published in 2014. Different authors have brought new perspectives on key topics, while the updated version also reflects a rapidly changing research landscape. While development in the field was once driven by hard disk-drive technology, magnetism and magnetic materials are now becoming increasingly important in energy generation and other technological fields.

More attention is also focusing on complex topologies of magnetically ordered states, with promising applications now emerging for the theoretical concepts that were recognized by the 2016 Nobel Prize in Physics. “The interconnecting roles of having suitable magnetic materials, understanding the underlying physics of their behaviour, and utilizing them for applications and devices is well illustrated, thus giving an accurate snapshot of the world of magnetism in 2017,” write the authors. J. Phys. D: Appl. Phys. 50 363001

Superconductor Science and Technology

New award recognizes early career researchers

A new annual award has been introduced by the journal Superconductor Science and Technology (SUST) to mark its 30th anniversary. The Jan Evetts SUST Award, named in memory of the journal’s founding Editor, recognizes the best papers published in the journal by early career researchers.

“Our Editorial Board and our team at IOP Publishing are dedicated to supporting early career researchers,” said SUST publisher Lucy Smith. “We are delighted to announce the winners of the 2017 award.”

- The submission window for the 2018 award will be open from 1 October 2017 until 31 March 2018.

THE WINNERS

1st prize
Ibrahim Kesgin, Argonne National Laboratory
High-temperature superconducting undulator magnets Supercond. Sci. Technol. 30 04LT01

2nd prize
Qing-Yuan Zhao, Massachusetts Institute of Technology
A nanocryotron comparator can connect single-flux-quantum circuits to conventional electronics Supercond. Sci. Technol. 30 044002

3rd prize
Min Zhang, Bath University
A New Ring-shape High Temperature Superconducting Trapped Field Magnet Supercond. Sci. Technol. 30 094002

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News from IOP Publishing

Open access journal takes interdisciplinary approach

A new multidisciplinary open-access journal that offers researchers an accelerated and innovative way to publish their work has been launched by IOP Publishing. Known as Journal of Physics Communications, it welcomes the submission of papers from all areas of research relating to physics. It has a particular interest in interdisciplinary studies that may not fit the narrower scope of traditional journals, and all authors will benefit from a fast, inclusive and transparent peer-review process.

Journal of Physics Communications is guided by a seven-strong senior editorial panel, who will work closely with the in-house editorial team to ensure that the journal meets its aim of high-quality peer review, rapid publication and inclusive coverage of all physics research. The editorial panel will provide final arbitration for scientific disputes and advice on emerging subjects.

“We are excited about the launch of this important addition to our programme, which is an innovative open access journal takes interdisciplinary approach

Peer review under the spotlight

Throughout 2017, IOP Publishing has been testing the merits of so-called double-blind peer review, in which the referee does not know who has submitted the article. Authors submitting papers to two journals – Biomedical Physics & Engineering Express and Materials Research Express – have been offered the option of choosing double-blind review or the more conventional single-blind approach, where the authors don’t know the identity of the reviewer, but the reviewer knows who has submitted the article.

The response from the community has been very positive, with around one in five authors choosing the double-blind option when submitting to both journals. In a survey of authors who submitted their articles for double-blind peer review, 95% of respondents rated the overall experience at better than 8 out of 10, with an average score of 9.5.

The vast majority of respondents, around 85%, said they chose the double-blind option because they think it is the fairest system of peer review. According to Simon Harris, one of three managing editors who oversee the peer-review process at IOP Publishing, peer-review times have on average been slightly shorter for double-blind articles than single-blind ones.

The pilot scheme will run until the end of 2017. “At the end of the year-long pilot, we’ll let the community know what we’ve learned, and whether or not we plan to continue with the double-blind option on our journals,” says Harris. “We will continue to monitor the take-up rate of the double-blind option, authors’ satisfaction with the process, and any effects on overall publication times.”

Journals mark major milestones

Some of our most established titles have celebrated significant anniversaries in 2017. The prestigious Journal of Physics series marked its 50th anniversary with a year-long programme of events and workshops across the world, while Superconductor Science and Technology celebrated its 30th year with the introduction of a new award for early-career researchers (see p31).

Two other journals, Modelling and Simulation in Materials Science and Engineering and Smart Materials and Structures, are celebrating their silver jubilee, while it is also the 10th year of Applied Physics Express (APEX), which we publish in partnership with The Japan Society of Applied Physics.
Ten Physics World Discovery ebooks released

IOP Publishing has launched a new resource for the physics community. Entitled Physics World Discovery, these short-form ebooks provide readers with succinct but expert introductions to some of the hottest topics in physics. Physics World Discovery titles replicate the style and editorial approach of Physics World, providing clear and accessible texts from leading voices across the scientific community.

The first 10 publications in the Physics World Discovery collection have been published, with topics including quantitative finance, proton beam therapy, complex light, space weather, the dark universe and multi-messenger astronomy. The Physics World Discovery collection will grow throughout 2017 and 2018, with each title freely available to the global research community on the IOPscience platform, where IOP Publishing’s journals, ebooks and Physics World content can also be found.

“The Physics World Discovery series provides exciting and accessible material to educate students and others about the latest challenges in fast-moving research fields,” says Catherine Heymans from the Institute for Astronomy at the University of Edinburgh in the UK, the author of The Dark Universe. “Thanks to Physics World’s reach and strong reputation for presenting physics in a way that is easy to understand, I was delighted to contribute to the Discovery series by writing about observational techniques to study dark matter and dark energy.”

Jamie Hutchins, publishing director at IOP Publishing, thinks Physics World Discovery is an “exciting experiment”, which allows authors to “create engaging material that helps readers of all levels to understand the importance of research in the physical sciences, and how it connects to broader societal issues”. Hutchins adds that Physics World Discovery is “straightforward for authors to write, published rapidly, and allows an interested reader to grasp new concepts and trends quickly”.

*View the Physics World Discovery collection at physicsworlddiscovery.org.*

**Rewards for Reviewers**

This year has seen the introduction of IOP Publishing’s Reviewer Awards, designed to celebrate the contributions of the very best reviewers across the previous year. The editors of each journal have selected one person to receive the Reviewer of the Year Award, based on the quality, quantity and timeliness of their reports, while a number of other excellent referees have been recognized with Outstanding Reviewer awards. All the award winners are listed in full on the individual journal pages on IOPscience, and more than 1400 of the 27,000 researchers who reviewed for IOP last year received an award. Winners came from 140 countries, with Ecole Polytechnique Federale de Lausanne in France and the University of Cambridge in the UK picking up the most awards, with eight and seven respectively.

IOP Publishing wishes to thank all our reviewers, and to recognize the essential rigour and validation they provide for all our published papers.

**Opening up to ORCID**

Ensuring that researchers get full credit for their work is an important priority for IOP Publishing, which means that we are now requiring all corresponding authors to include ORCID identifiers when submitting their work to our journals. ORCID IDs will be collected for all titles owned by IOP Publishing during the submission process, allowing researchers’ ORCID records to be automatically updated when their articles are published.

Open Researcher and Contributor ID, known as ORCID, is a not-for-profit organization that provides scholars with a unique digital identifier that distinguishes them from other researchers with similar names. By connecting this identifier to all their research activities, publications, and affiliations, scientists can be sure that they will be fully recognized for all their work. Several major funders are also now requiring ORCID IDs as part of their grant application process.

“It is extremely important that researchers are correctly recognized for their work, whether as an author, reviewer or editor, and that the community is able to cite work without confusion,” says Jamie Hutchins, Publishing Director for IOP Publishing. “ORCID identifiers make this easier, by removing the confusion that can be caused by similarities between researchers’ names, name changes, movement between institutions, inconsistencies in abbreviations, and cultural differences in how names are presented.”

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**News from IOP Publishing**

**Materials: from research to technology and innovation**

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To find out further information about our materials science journals, visit iopscience.org/materials.
## Materials science journals

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Video abstracts allow authors to personally present the importance of their work, and also offer an opportunity to integrate live demonstrations of both experiments and simulations into the journal article. Authors are invited to submit their videos to 2D Materials, New Journal of Physics, Reports on Progress in Physics, and Methods and Applications in Fluorescence.

IOP Publishing has partnered with Publons, a reviewer recognition service that enables referees to track, verify and showcase the reviews they submit through the Scholar One system. Reviewers for participating journals have the option to add a verified record of each review to their Publons profile, even if the manuscript is never published. By default, only the name of the journal and the year of the review are displayed on Publons to protect the anonymity of the reviewer.

IOP Publishing is now offering authors the choice of single- or double-blind peer review on Materials Research Express and Biomedical Physics & Engineering Express as part of a pilot scheme that will run to the end of 2017. Feedback from the research community suggests that there is a growing demand for the double-blind review option (in which the reviewer does not know the identity of the author), and through this pilot scheme we aim to gain specific insight into uptake in the broad area of materials science.

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Adding value to IOP authors

IOP Publishing in the news

As part of our ongoing commitment to help gain recognition for authors and their work, we regularly highlight published articles to the news media, resulting in a broad range of print, online and broadcast coverage.

Here are just a few examples of materials science articles published in IOP Publishing journals that have made the headlines:

**HEADLINE ARTICLES**

- **Nanomaterials help spiders spin the toughest stuff**
  Researchers from the UK and Italy used carbon nanotubes and graphene to allow spiders to produce silk three times tougher and 10 times stronger than normal.
  - iNews • ZDNet • New Atlas • Yahoo News • Sydney Morning Herald
  - **Emiliano Lepore et al 2017 2D Mater. 4 031013**

- **Colour-shifting electronic skin could have wearable tech and prosthetic uses**
  Chinese researchers developed a new type of user-interactive electronic skin, with a colour change perceptible to the human eye, and achieved with a much-reduced level of strain. It has applications in robotics, prosthetics and wearable technology.
  - ScienceDaily • BreakingNews.ie
  - **Tingting Yang et al 2017 2D Mater. 4 035020**

- **Solar cell breakthrough paves the way for new applications**
  An international scientific collaboration has successfully integrated a sub-micron thin, nanophotonic silicon film into a crystalline solar cell for the first time.
  - The Engineer • PV Magazine • Phys.org
  - **Valérie Depauw et al 2017 Nano Futures 1 021001**

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**Introductory guide for authors**

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