MATERIALS IN 2020

DECEMBER 2020

What's shaped this year's materials world

Research in the time of covid-19

Energy materials
Latest advances in batteries, fuel cells and perovskite solar cells

Quantum materials
Breakthroughs in quantum computing and superconductors

Biomaterials
From disposable nappies and optical fibers to super-glue and bone repair

Interviews
How did leading materials scientists cope with the disruption caused by the pandemic

Introduction

MATERIALS IN 2020 looks back on what has happened in this strangest of years

BY ANY MEASURE, 2020 has been a funny old year. But amid all the disruption and difficulties caused by the covid-19 pandemic, materials science has kept on going – research has continued to be conducted and findings published. Materials scientists may have had to change how they work, but they have still continued to work, and this is reflected in all the advances and developments that have occurred this year.

Materials in 2020 looks back on what has happened in the materials science field in this strangest of years. It contains features on developments in five important areas of materials research – lithium-ion batteries, energy storage, perovskite solar cells, quantum materials and biomaterials. These five features are not intended as comprehensive reviews, but just to provide a snapshot of the kind of research that was published this year and to highlight some of the main trends and themes. As such, the features roam widely, covering everything from room-temperature superconductors to flow-cell batteries to spider silk.

The magazine also contains interviews with four leading materials scientists to discover how they and their research have fared this year. Encouragingly, although the pandemic obviously had an impact, all four managed to keep their research activities going to some extent throughout the year, with three of them even finding ways to apply their materials research to the struggle against the SARS-CoV-2 virus.

This hopefully suggests that advances and developments in materials science should continue coming in 2021, particularly if it turns out to be a bit less of a funny old year.

Jon Evans
Editor of *Materials in 2020*

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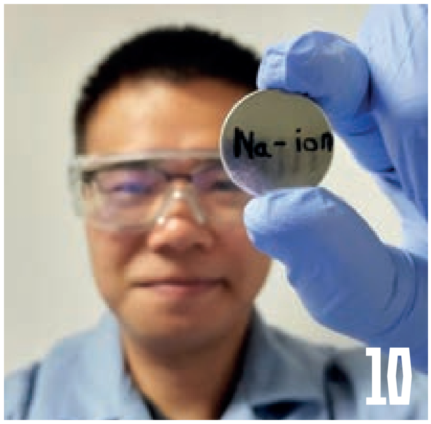
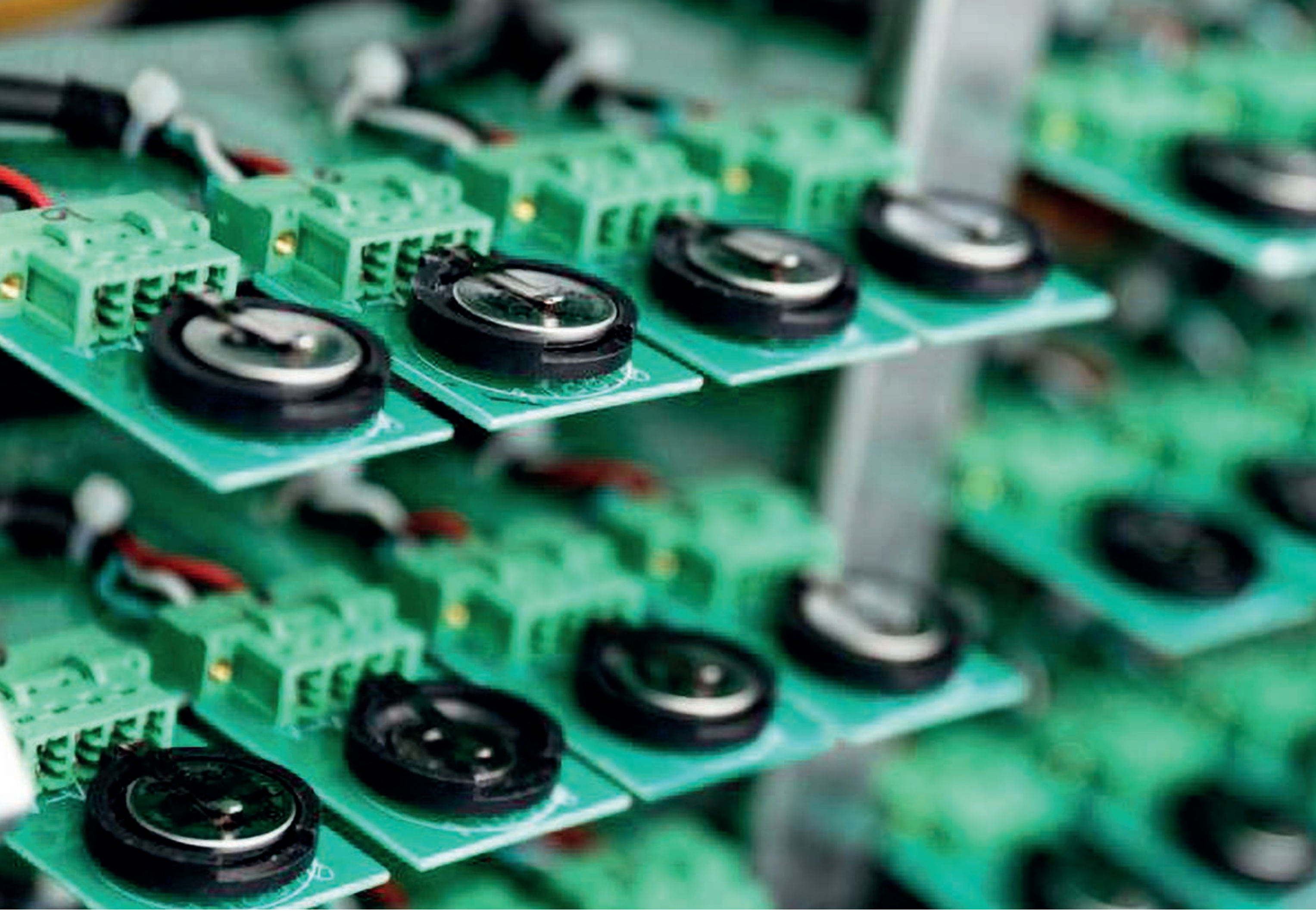


MATERIALS IN 2020

EDITOR Jon Evans, **DESIGNER** Nick McKay, **CONTRIBUTORS** James Bakewell, Rachel Brazil, Maria Burke, Emma Davies, Jon Evans, Fernando Gomollón-Bel. *Materials in 2020* was produced for *Materials Today* by JES Editorial Ltd.



Developments in lithium-ion batteries

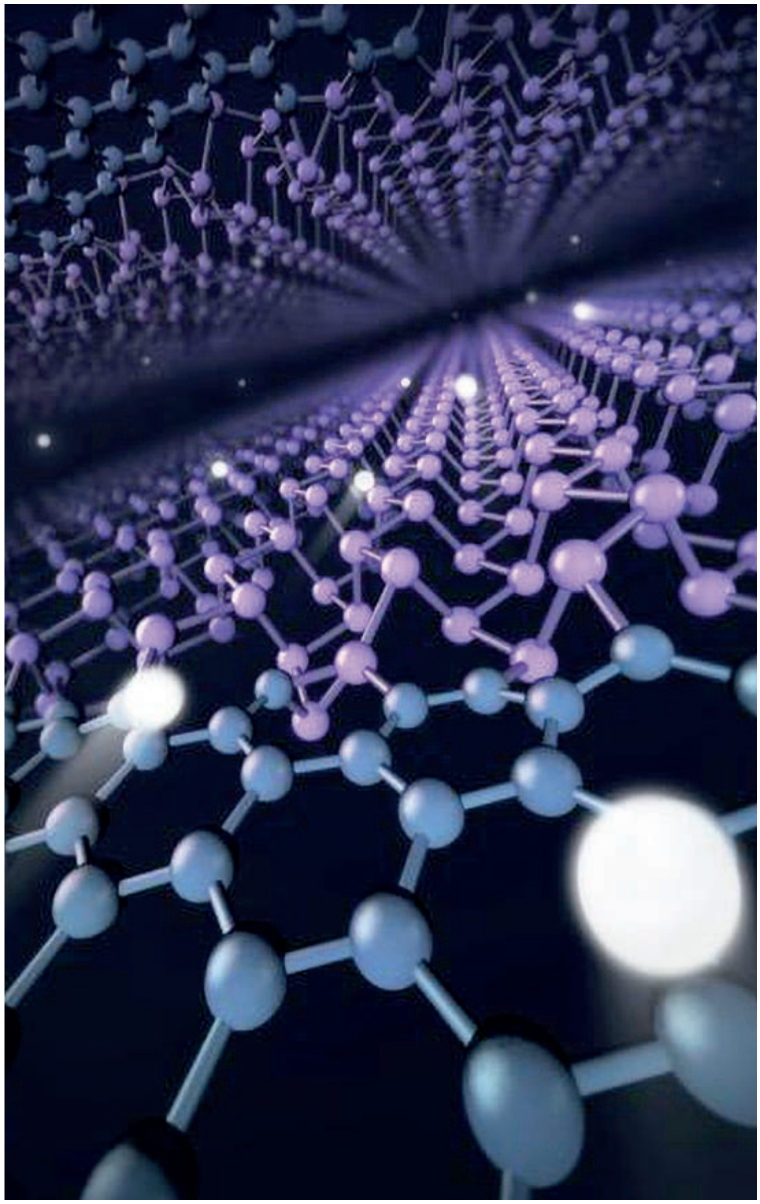
In 2020, scientists continued to work on improving every component of the lithium-ion battery, as well as developing the next generation of lithium-based battery technologies

UNIVERSITY OF CAMBRIDGE

WHILE THE lithium-ion battery continues to be the battery technology to beat in 2020, there is increasing demand for improved versions with greater capacity and longevity for use in both electric vehicles and photovoltaic-battery power plants. The aim of much current research is to increase battery energy density to greater than the current 350 watts-hour per kilogram (Wh Kg^{-1}) limit, sufficient to allow an electric car to travel 300 miles, but there are also continuing efforts to increase safety, speed of charging and battery life.

In lithium-ion batteries, electricity is generated by the flow of lithium ions between two electrodes – an anode and a cathode – through an electrolyte. Current versions usually utilize a layered oxide cathode, most commonly lithium cobalt oxide ($LiCoO_2$), a graphite anode and an electrolyte comprising lithium hexafluorophosphate ($LiPF_6$) in an organic solvent.

To prevent short circuits, the electrodes are separated by a very thin microporous polymer separator that still allows the flow of lithium ions during charging and discharging. But this polymer separator can be punctured by lithium dendrites – microscopic lithium metal needles that form when lithium builds up on the anode surface if the battery is overcharged – causing a short circuit and leading to battery fires and explosions.



DONG YIHAN, SHI QIANHUI AND LIANG YAN

Electrodes

Preventing the formation of lithium dendrites is one of the key drivers for research into novel anode materials, along with improving energy storage capacities and charging rates. Graphite has a relatively low charging rate, and so several research groups are considering other carbon-based anodes, including highly conductive, lightweight carbon nanotubes (*Nano Letters*). In October, a group from China published results from a black phosphorous and graphite composite anode with increased energy density, which would allow an electric car to travel 600 miles on a single charge (*Science*, see image).

A great deal of anode research is focused on silicon, which has an exceptional capacity for intercalating lithium ions, allowing it to hold 10 times more charge then graphite. But this exceptional capacity for lithium ions can cause silicon anodes to expand by up to 280% during charging, which leads to cracking and disintegration of the electrode (graphite expands by only 10%).

One solution is to blend silicon with carbon. In August, US scientists developed an anode made from silicon nanoparticles sandwiched between layers of a carbon nanotube material called Buckypaper. This anode held together after 500 cycles, and could be charged at a higher current and four times faster than current lithium-ion batteries (*ACS Applied Materials & Interfaces*). A team from Finland reported a composite anode made from carbon nanotubes and mesoporous silicon microparticles, sustainably produced from barley husk ash (*Scientific Reports*), while another US team used carbon nanotubes coated with silicon microspheres. (*Nature Communications*, see image).

Other new anodes are being investigated for analogues of the lithium-titanate battery (LTO) – a modified lithium-ion battery that uses lithium-titanate nanocrystals on the surface of its anode. It has a lower energy density than conventional lithium-ion batteries, but charges much faster and is considered safer. In September, a US team showed that a lithium vanadate ($Li_3V_2O_5$) anode could deliver over 40% of its capacity in 20 seconds. The fast rearrangement of lithium ions in the material results in faster lithium diffusion. (*Nature*). »

LEFT **Lithium-ion coin cell batteries being tested**

RIGHT **Structure of the black phosphorous and graphite composite anode**

With cathodes, researchers are looking to eliminate cobalt, due to its high cost, and find alternative materials that can intercalate more lithium. Nickel-rich compounds offer higher capacities, but degrade much faster than existing technologies. In August, a UK team suggested this was due to surface atom rearrangements over multiple rounds of charging, which subsequently prevent lithium ions leaving the cathode (*Nature Materials*). The team is now looking at protective coatings and electrolyte additives to stop these damaging changes. A US team found that mixed iron, nickel and zinc oxide cathodes could produce up to three times the charge capacity of commercially available lithium-ion batteries – through surface absorption of lithium ions onto iron nanoparticles formed during charging and discharging (*Nature Materials*).

The role that oxygen plays in cathode processes has become another focus of research. As lithium ions are removed, oxide ions in the cathode material become oxidized, but this process is not fully reversible in all materials, which can lead to a loss of energy density. Research teams have been looking for materials that allow fully reversible lithium removal. In September, an Oxford team showed that if molecular oxygen could be trapped inside the bulk cathode, the oxide could be fully reformed (*Nature Energy*).

Electrolytes

One of the weak links in current battery technology is the use of highly flammable organic liquid or gel electrolytes. Understandably, they pose safety issues, but finding solid-state electrolytes with high enough room-temperature ionic conductivity has not been easy. One option is high conductivity ceramic materials, but they can be brittle. A study in July proposed infusing a ceramic known as LATP (Li_2O–Al_2O_3–TiO_2–P_2O_5) with graphene to increase its strength (*Matter*,). A Canadian group has looked to exploit the 'paddle-wheel' effect, with conductors such as β-Li_3PS_4. These conductors contain polyanions that rotate within the electrolyte framework, dramatically speeding up lithium ion diffusion (*Matter*).

Another option is composites. For example, a Swedish and Chinese team produced a spreadable 'butter-like' material formed from an ionic liquid encapsulating ceramic nanoparticles (*Advanced Functional Materials*).

One of the weak links in current battery technology is the use of highly flammable organic liquid or gel electrolytes

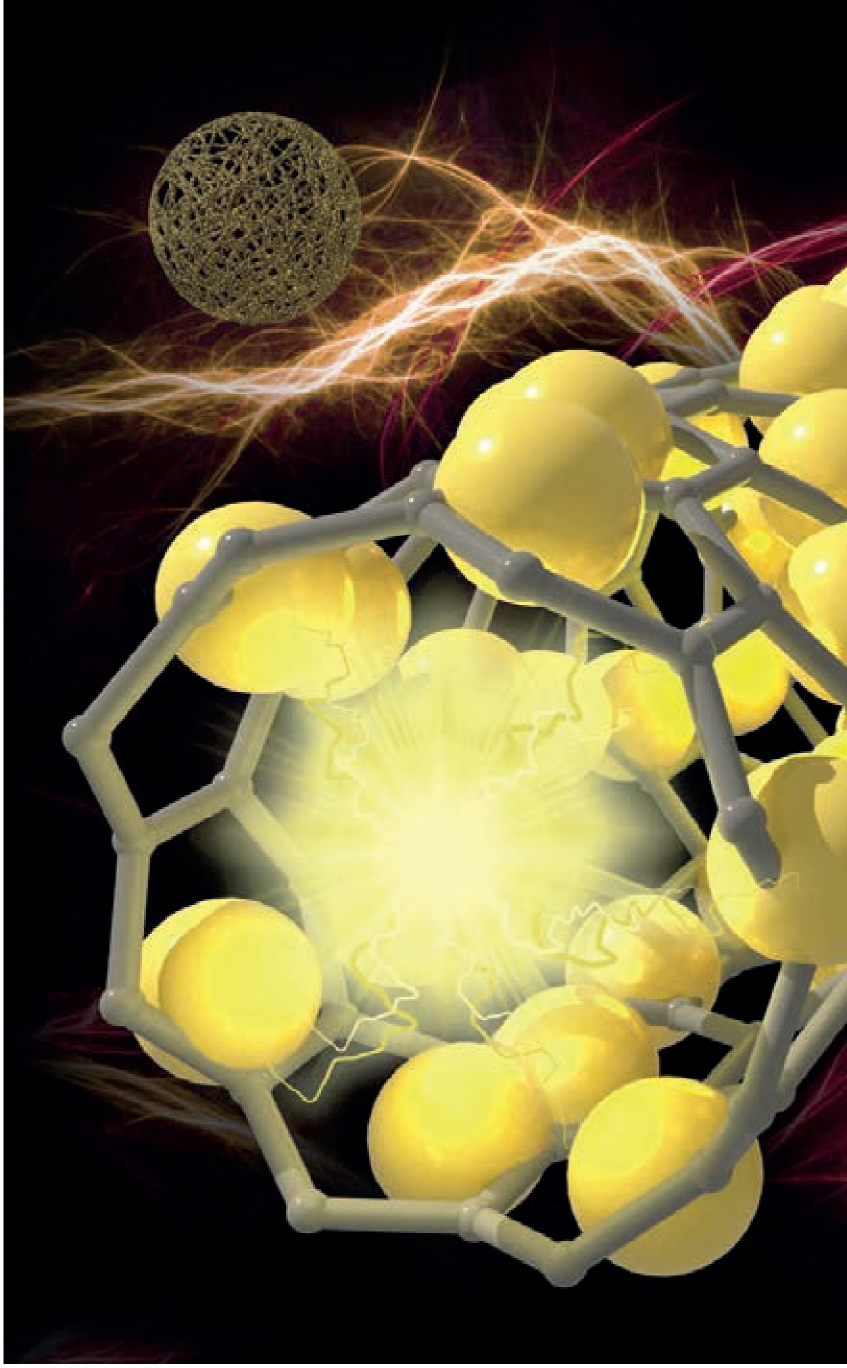
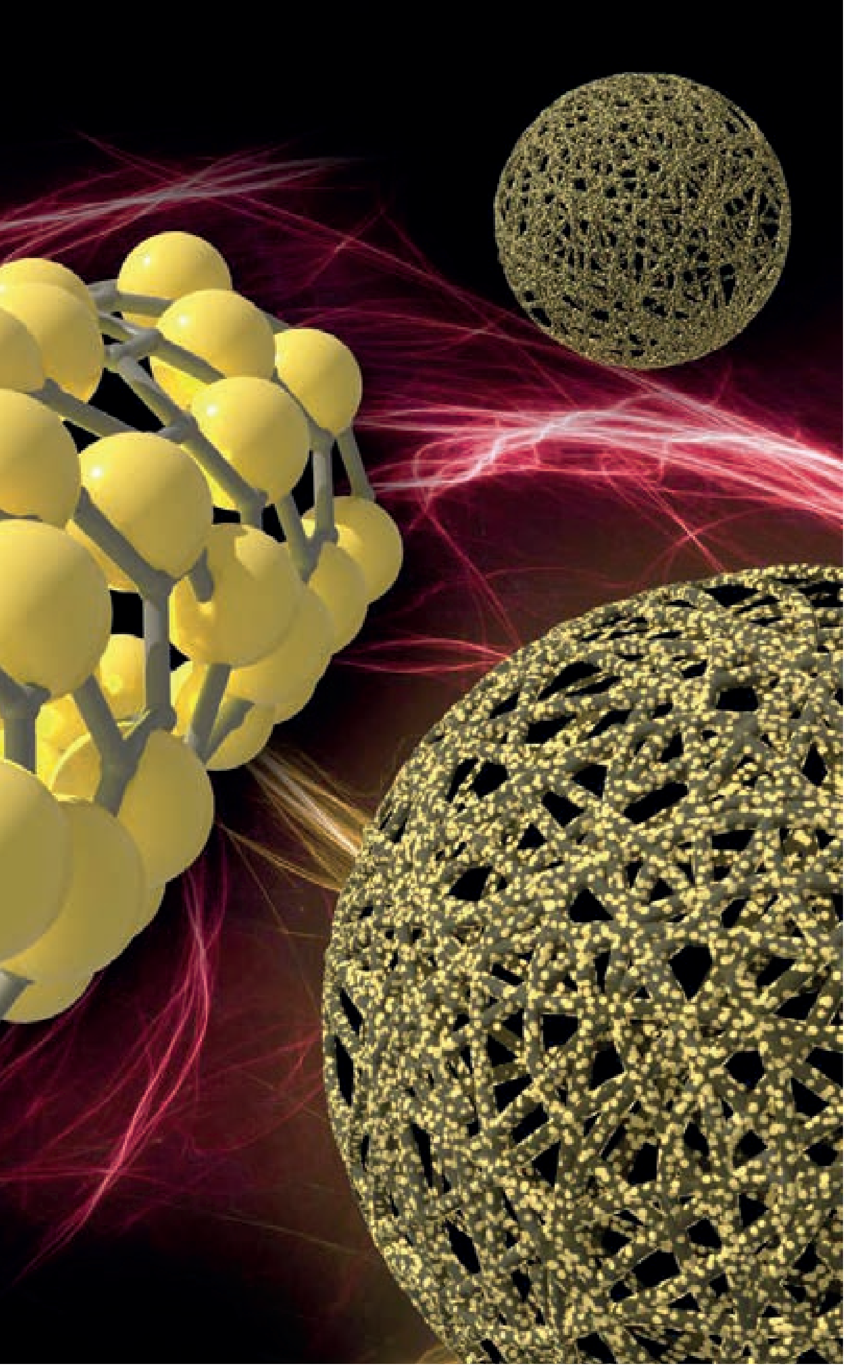


Illustration of the anode made from carbon nanotubes coated with silicon microspheres

Meanwhile, a US group reported a new class of soft solid electrolyte made from porous polymers filled with ceramic nanoparticles, which successfully suppressed dendrite formation (*Nature Materials*).

As well as battery materials that are safer and more efficient, researchers have been actively developing materials that are more flexible, for use in wearable electronic devices. For example, a US team reported a new stretchable battery that maintained a constant power output even when squeezed or stretched to nearly twice its original length. This utilizes a novel polymer electrolyte, and the current prototype can store half the energy of a conventional lithium-ion battery. (*Nature Communications*).

Russian researchers proposed a method for inkjet printing lithium-manganese-rich compounds as cathodes, reducing the electrodes' thickness by 10–20 times.



MICHAEL PERKINS/PNNL

(Energy Technology). A South Korean group developed a stretchable lithium-ion battery using accordion-like micro-honeycomb graphene–carbon nanotube composite electrodes and a stretchable gel electrolyte. (ACS Nano).

Other lithium technologies

Researchers are also continuing to explore more fundamental modifications to the lithium-ion battery. A lithium-metal battery, where the anode itself is made from lithium, could theoretically hold about twice as much electricity per kilogram as today's lithium-ion batteries, but significant design problems have limited its development. Oxidation of the lithium anode surface leads to fast degradation and failure after only 30 cycles, and lithium anodes are even more prone to dendrite formation.

Silicon anodes can hold 10 times more energy than graphite anodes

10

In June, a US team reported a new, more stable fluorinated electrolyte that could solve these problems. A lithium-metal battery using this electrolyte retained 90% of its initial charge after 420 charging cycles – not as good as an equivalent lithium-ion battery, but one of the best performing lithium-metal batteries to date (Nature Energy). Another solution, from a US group, involved depositing a porous silicon oxide and graphene layer between the lithium-metal anode and the copper current collector. This coating suppressed the formation of dendrites and tripled the battery's lifetime (Advanced Materials).

A lithium-air battery could be the biggest game-changer. Rather than inserting lithium ions into a cathode, these batteries utilize a chemical reaction – the reduction of ambient oxygen introduced through a carbon fiber membrane – which provides a greater electron transfer and a massive theoretical energy density of 12,000Wh Kg^{-1}.

So far, however, efforts to utilize such systems have failed due to a build-up of insoluble lithium peroxide films, which poison the lithium anode. In January, a Korean team improved on previous lithium-air batteries by using a composite cathode made from nickel cobalt sulphide nanoflakes and porous graphene doped with sulphur to improve charge transport. The large number of active sites in this cathode seemed to stop the formation of lithium peroxide, allowing the battery to deliver an ultra-high discharge capacity for over two months (Applied Catalysis B: Environmental).

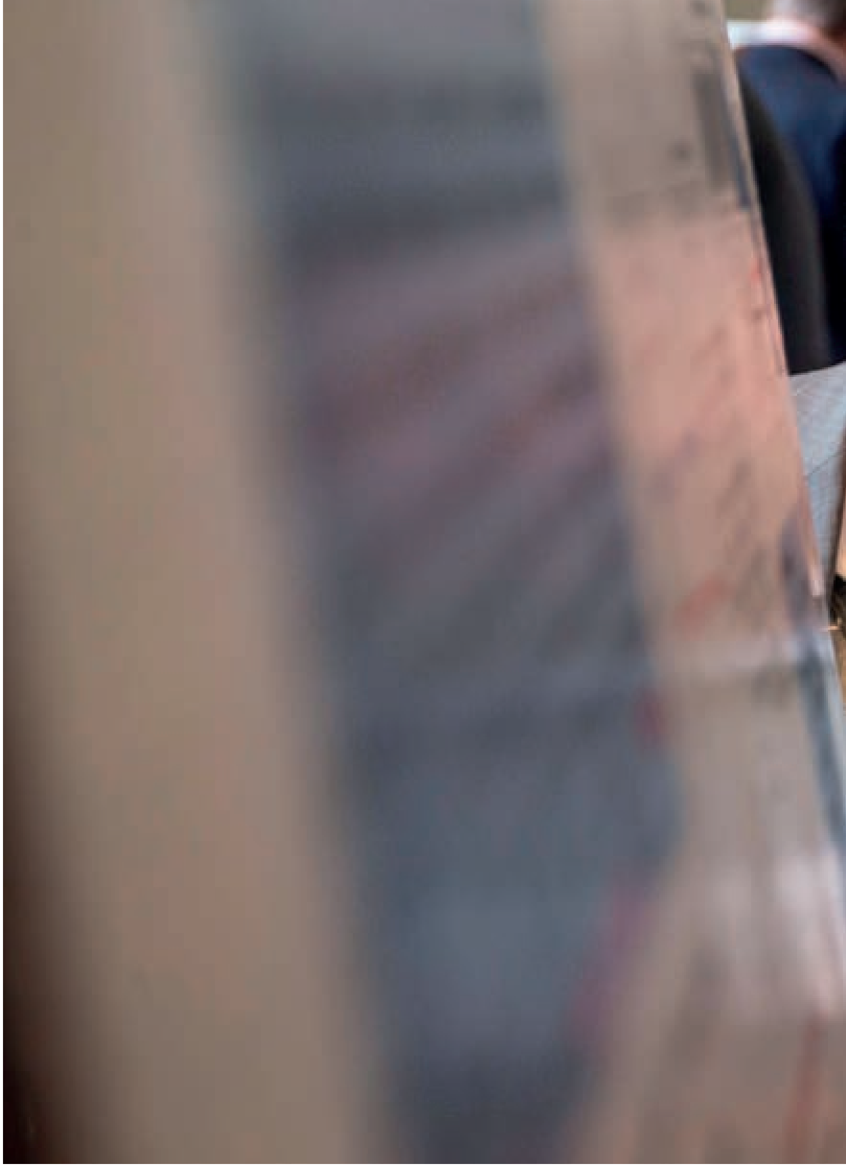
Closer to commercialization is the lithium-sulphur battery, which is composed of a sulphur-based cathode and a lithium anode submerged in a liquid electrolyte. With an energy density of 2600Wh Kg^{-1}, these batteries have the potential to outperform lithium-ion batteries, while also being more sustainable and cheaper. They are also safer, as dendrites tend to dissolve away during charging and discharging.

Despite this, lithium-sulphur batteries suffer from poor cycle life and low energy efficiency due to the formation of lithium polysulphides (LiPS) during discharge, known as 'polysulphide shuttle', which progressively degrades the battery capacity. In June, a Korean group reported a non-conductive, sulfur-rich mesoporus silica cathode that could trap polysulfides, which demonstrated outstanding long-term stability over 2000 cycles (Advanced Energy Materials). Meanwhile, a Japanese team successfully designed a fully solid-state lithium sulphur battery with a composite carbon nanofiber and sulphur nanosheet cathode (ACS Applied Energy Materials).

In 2021, lithium-ion batteries will be 30 years old, and yet lithium-based battery technologies remain a highly active research area, suggesting they will still be the battery technology to beat for some time to come. ●

Still charging ahead

The covid-19 pandemic may have slowed them down slightly, but Chunsheng Wang and his group have continued to publish important work on lithium-ion batteries and win major grants



ON PAPER, 2020 has been a great year for Chunsheng Wang, a battery expert at the University of Maryland, US. In the spring, he published a widely reported study with the US Army Research Laboratory (ARL), describing a way to significantly boost the capacity of lithium-ion batteries. In July, he was awarded a $1 million grant by the US Department of Energy (DoE) for the next phase of his battery work. But the covid-19 pandemic has brought challenges, with limited lab time and difficulties recruiting new post-docs.

Wang likes to approach battery problems from an electrolyte angle. In 2015, together with ARL colleagues, his team published ground-breaking research in Science, reporting new ways to make aqueous lithium-ion batteries using a water-in-salt electrolyte (WiSE).

Traditional lithium-ion batteries have long caused safety concerns because they contain flammable organic electrolytes and can burst into flames under certain conditions. Non-flammable aqueous electrolytes are a natural replacement but had been held back by limited stability. WiSE appeared to be a solution, improving stability over 1000 battery cycles of charge and use.

Over the past three years, Wang's group has significantly reduced the concentration of the lithium salt in the WiSE to bring costs down. He is also collaborating with global battery manufacturer Saft. The plan is for Saft to put the technology into a cell which the ARL can then put through vehicle safety tests for durability and flammability, especially when under fire.

Boosting capacity

Another branch of Wang's work with ARL focuses on improving electrode materials in lithium-ion batteries to boost capacity.

For example, replacing standard graphite anodes with silicon anodes can increase capacity almost 10-fold. But silicon anodes degrade more rapidly than graphite ones and also tend to expand during battery use, which cracks their protective layer, known as a solid electrolyte interphase (SEI). This happens because the silicon binds strongly to the SEI. Previous research efforts had mainly focused on modifying the silicon structure, using expensive nanofabrication processes.

Wang and his colleagues approached the problem by designing a fluorinated electrolyte that forms a rigid lithium fluoride SEI when it interacts with silicon anode particles. This SEI only binds weakly to the silicon and so allows the anode to expand without causing damage.

This year, the team published a paper suggesting that the self-healing, protective SEI layer could extend the lifespan of lithium-ion batteries by minimizing electro-

There is hope that the SEI technology could even be applied to solid-state batteries, helping to prevent the growth of damaging lithium dendrite structures

"WE REALLY PRODUCE SOMETHING USEFUL FOR THE BATTERY COMMUNITY."

ARPA-E

lyte degradation (Nature Energy). This technology also allows thinner electrodes and a lighter battery, which should be able to withstand colder temperatures than today's batteries.

The SEI technology could also be used with other types of high-capacity anodes, says Wang. For example, his Maryland team recently showed that it works with lithium metal, the "most competitive" anode material for next-generation batteries (Advanced Materials).

There is hope that the SEI technology could even be applied to solid-state batteries, helping to prevent the growth of damaging lithium dendrite structures. The mechanisms responsible for the formation of dendrites are still not fully understood, but they can cause lithium batteries to short circuit and catch fire.

Thinking deep

During the pandemic's first lockdown in the US, the University of Maryland closed its campus from March to July. "I tried to use this time to think deep," says Wang. He also encouraged his students to do the same.

When the labs reopened in July, they were only at 50% capacity, with students taking turns to work in mornings or afternoons. These time limits have meant that Wang and his students have to be highly selective with experiments and focus only on the "most useful" topics. With less time in the lab but more time for discussions, they are still making good progress, he says.

When some of his post-docs left after their contracts had run out, Wang was initially unable to hire new researchers internationally because of visa restrictions. Although some restrictions have now been lifted, he is currently looking to recruit in the US to ensure continuity, particularly now that his DoE project on micro-sized silicon anodes has begun, with quarterly reports expected.

With the lithium battery field being "really, really competitive" and all major universities having an energy programme and a lithium-ion battery programme, it is not always easy to find the right candidates, he says.

Thankfully, Wang and his colleagues are still able to do the research that they want to do. "I still feel happy. We really produce something useful for the battery community," he says. ●

1000

WiSE improves stability over 1000 battery cycles of charge and use

Developments in energy storage

Researchers explored various approaches to energy storage in 2020, utilizing a wide range of different materials, from carbon nanotubes to mining waste to spinach

Junhua Song at Washington State University holds up a prototype sodium-ion battery

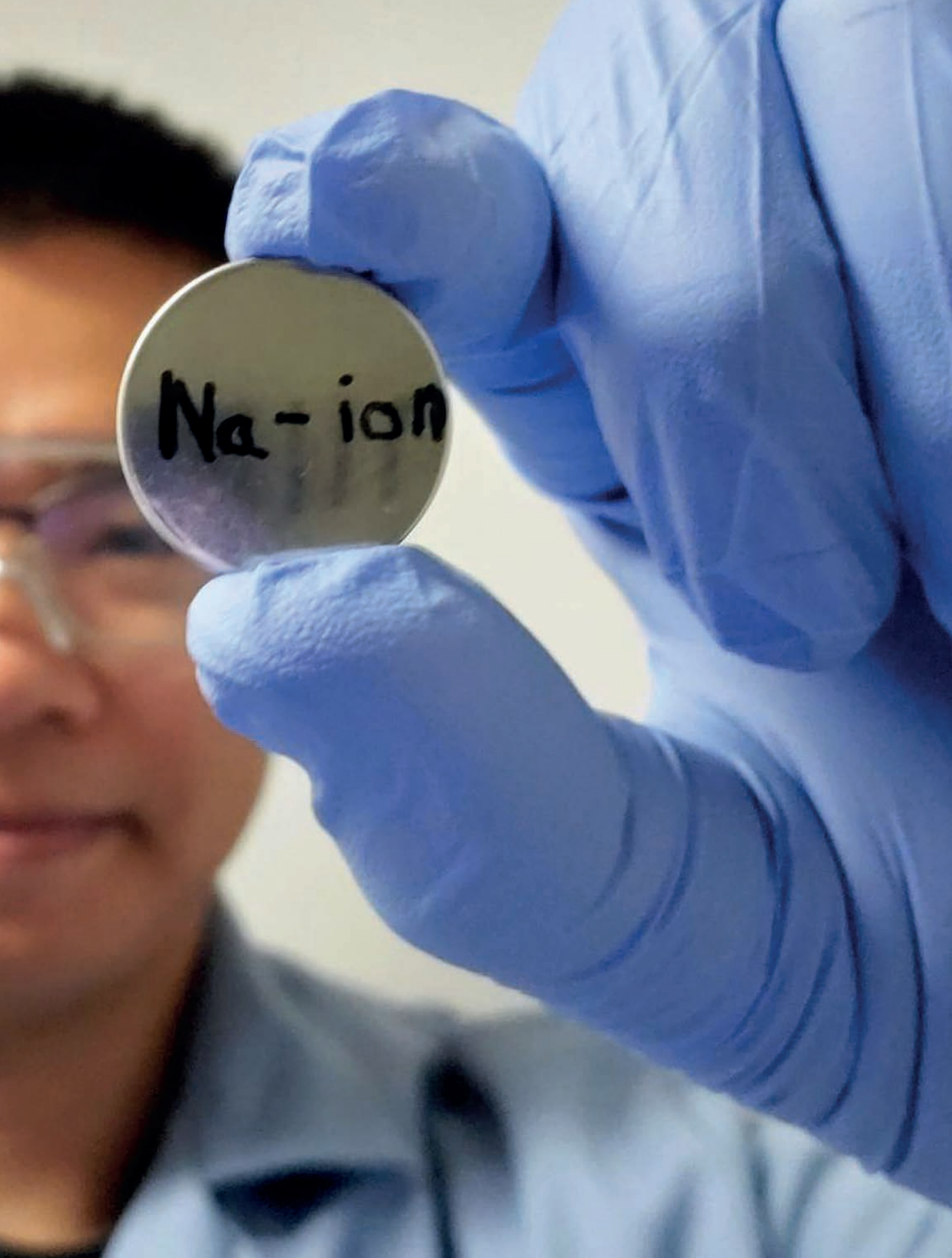
WSU

AS WELL AS continuing to explore ways to improve lithium-based batteries in 2020 (see *Developments in lithium-ion batteries*), researchers have also continued to develop other energy storage technologies. Many of these are battery technologies, but just ones that generate electricity via the flow of ions other than lithium, but others are completely different technologies that offer the promise of taking energy storage into completely new areas.

One of the main problems with lithium-based batteries is borne out of their own success. The ever-rising demand for lithium-ion batteries to power portable electronic devices and now electric cars is leading to spikes in the prices of the metals – principally lithium and cobalt – essential for their manufacture. Finding reliable alternatives to these expensive metals has therefore been a key focus of research in 2020. Of these alternatives, sodium is beginning to look like a real contender, according to a group of researchers based in Europe, who report that the metal is cheap, readily available and sustainable to use (*Journal of Power Sources*).

Unfortunately, current sodium-ion batteries do not hold as much energy as their lithium-ion counterparts and they are also not as re-chargeable. A key problem is that a layer of inactive sodium crystals tends to accumulate on the surfaces of the cathodes over time, hampering the flow of sodium ions within the batteries and, consequently, killing their performance. Looking to solve this problem, a research team in the US has created a layered metal-oxide cathode and a compatible liquid electrolyte that together serve to prevent this crust of sodium crystals from building up, allowing the »

Current sodium-ion batteries do not hold as much energy as their lithium-ion counterparts and they are also not as re-chargeable


Na-ion

sodium ions to move unimpeded. The resulting sodium-ion battery possesses a capacity similar to that of some lithium-ion batteries, and can retain more than 80% of this capacity after being charged and discharged 1000 times (*ACS Energy Letters*, see photo).

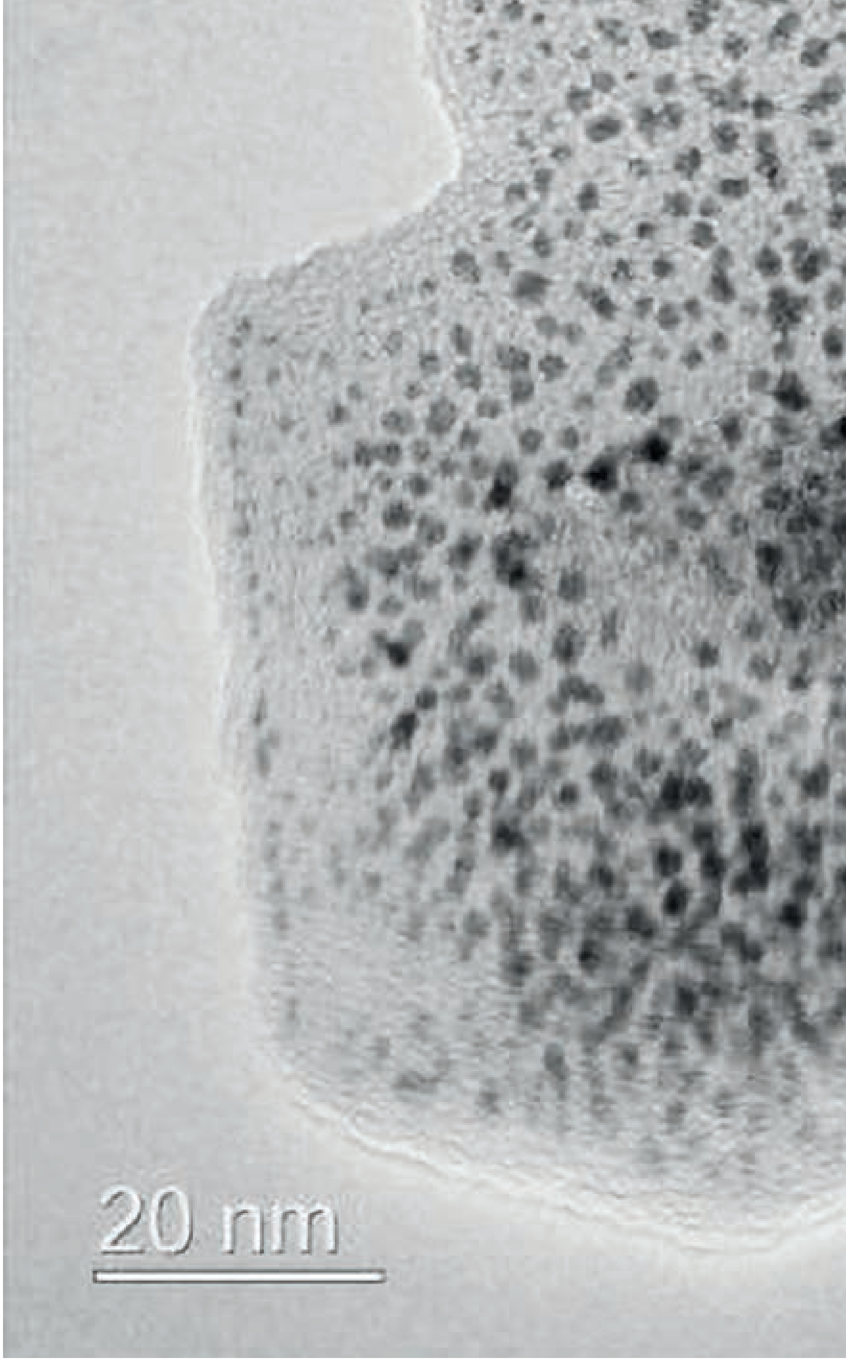
Other hurdles still remain, however. While graphite is widely used as an anode material for lithium-ion batteries, it has little capacity for storing sodium ions. Looking to gain a better understanding of the mechanisms underlying the performance of such components in sodium-ion batteries, researchers in the UK are using magnetic resonance imaging (MRI) scanners to observe the behaviour of sodium ions in electrodes as they go through charging and discharging cycles, allowing them to identify any degradation and points of failure as they occur (*Nature Communications*).

Several metal ions are also being considered as replacements for lithium, especially metals that are more abundant and cheaper. These include zinc, magnesium, calcium and aluminum (*Nature Energy*).

Super storage

Despite significant advances in recent years, lithium-ion batteries can still be slow to recharge. Supercapacitors, on the other hand, can be recharged in seconds and can withstand many more charge-discharge cycles before their performance starts to deteriorate. Further, they demonstrate high power density—they are capable of delivering a lot of power in quick bursts. Mobile phones and tablets, and even cars, fitted with these devices could be charged fully in the time it takes to make a cup of instant coffee. Unfortunately, supercapacitors exhibit low energy density, meaning they are unable to store sufficient amounts of energy to power these devices for any length of time.

Supercapacitors typically consist of two electrolyte-soaked electrodes separated by an ion-permeable membrane (separator), allowing them to store electrical charge directly on the surface of the electrodes. By tinkering with the materials from which these components are made, researchers have this year made significant progress in improving the performance of these devices. A team in the UK, for instance, has developed a three-layer composite electrode made of carbon nanotubes, a cheap, electrically conductive polymer called polyaniline (PANI) and hydrothermal carbon, which demonstrates remarkable rate-capability (it exhibits little voltage loss) at high energy densities (*Energy & Environmental Materials*).



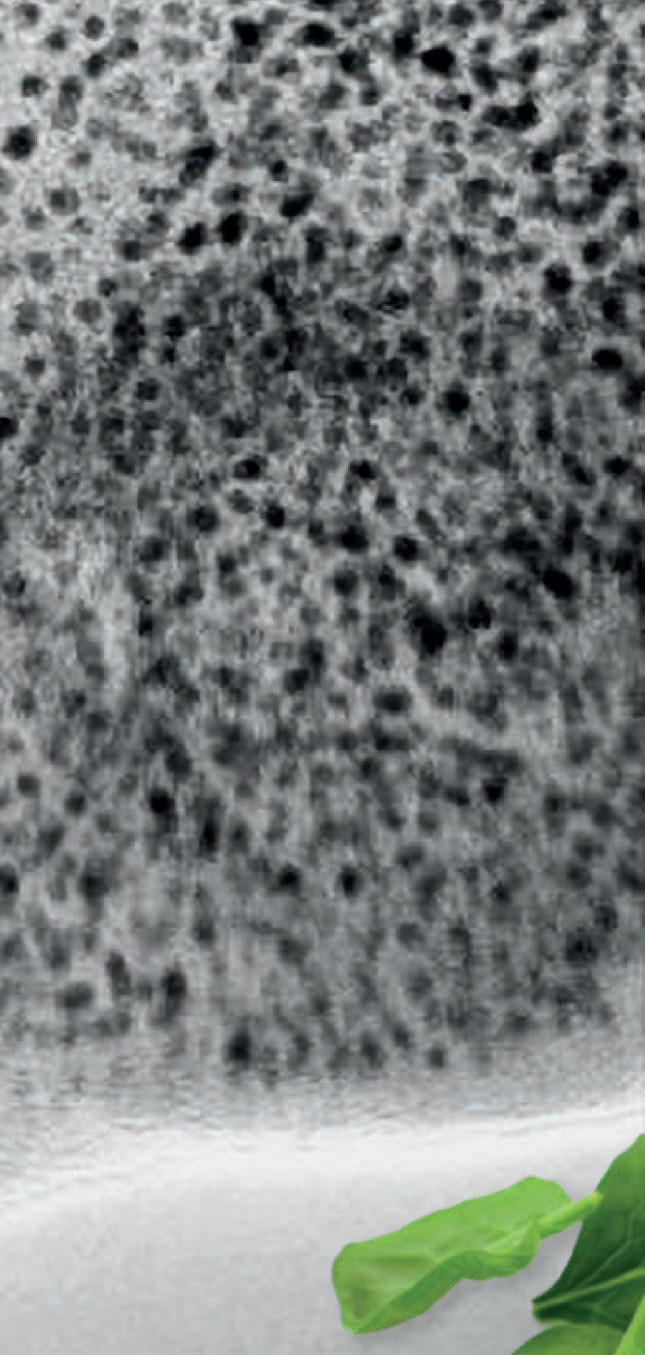
Supercapacitors can be recharged in seconds and can withstand many more charge-discharge cycles before their performance starts to deteriorate

There is also the hybrid supercapacitor, which can be recharged rapidly like a supercapacitor, but has the energy density of a lithium-ion battery. This year, researchers in Austria reported the development of a particularly sustainable form of such a device, comprising nanoporous carbon electrodes and an electrolyte of aqueous sodium iodide (*Nature Communications*).

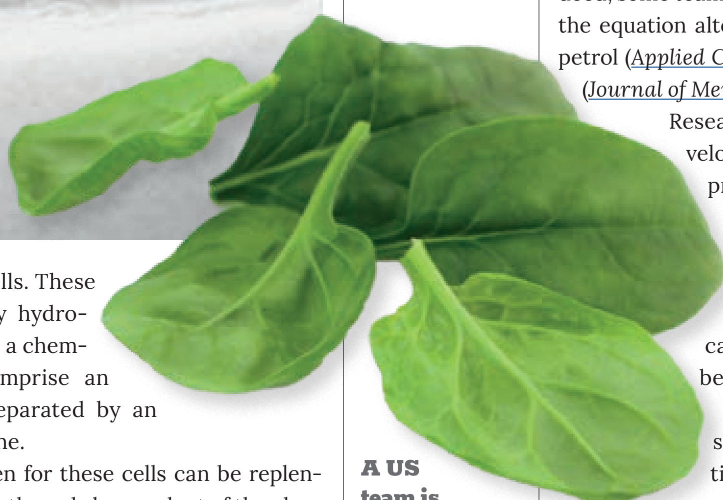
Filling up with hydrogen

While the lithium-ion battery in the latest mobile phones might take 30–45 minutes to re-charge fully, the battery of an electric vehicle can take 12 hours—promoting great interest in an alternative energy-stor-

PATRICK CULLEN / GYEN MING ANGEL



A transmission electron micrograph of graphene decorated with platinum nanoparticles for use in fuel cells



A US team is developing methods for producing durable carbon-nonosheet supports from, of all things, spinach

age technology: fuel cells. These convert a fuel, usually hydrogen, into electricity via a chemical reaction, and comprise an anode and cathode separated by an ion-exchange membrane.

The store of hydrogen for these cells can be replenished in minutes, and as the only by-product of the electricity-generating reaction is water, they represent an efficient and environmentally friendly power source. Their widespread adoption, however, has been somewhat hampered by issues regarding their long-term performance and the supply of hydrogen.

Proton-exchange membrane fuel cells (PEMFCs), for example, rely on catalysts based on expensive platinum to generate electricity. To reduce costs, commercial catalysts typically comprise platinum nanoparticles carried on a carbon support, but these hybrids are not particularly durable and break-down over time—reducing the lifetime of fuel cells. After identifying the mechanisms driving this degradation, researchers in the US found they could increase the stability of these catalysts by adding a gold underlayer to the platinum nanoparticles (*Nature Materials*).

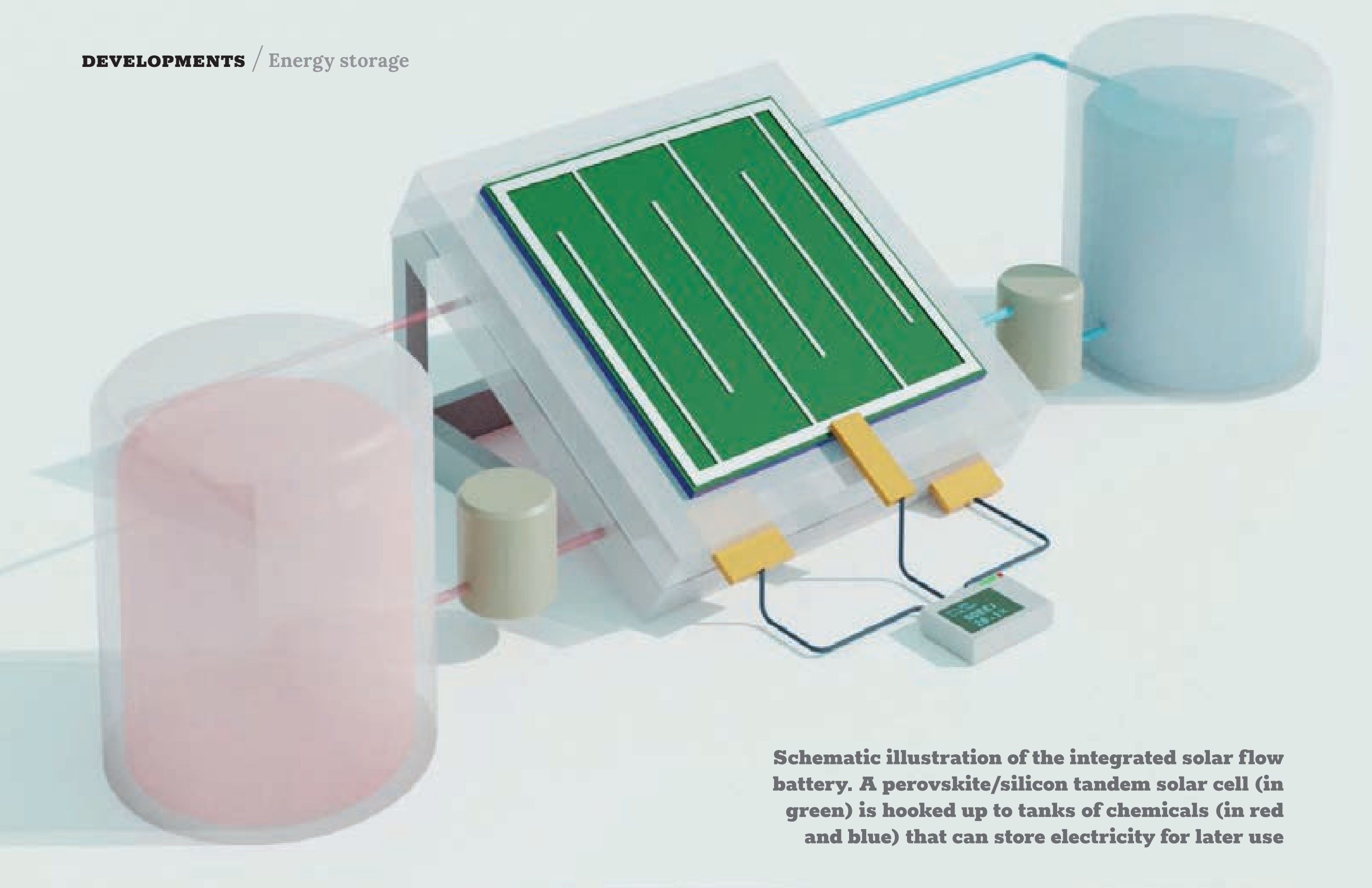
Another US team is developing methods for producing durable carbon-nanosheet supports from, of all things, spinach (*ACS Omega*). Researchers in the UK, meanwhile, have attempted to solve this problem by developing durable graphene-based supports (*Nanoscale*, see photo).

Taking a different approach, a research team in the US is looking to improve the performance of PEMFCs by modifying their ion-exchange membranes. These are typically made from perfluorinated sulfonic acid (PFSA) polymers that possess high mechanical strength but tend to block the oxygen needed by fuel cells to generate electricity, leading to significant energy losses. To solve this problem, the researchers created a novel copolymer: one part conducts ions, while the other is highly permeable to oxygen (*Journal of the American Chemical Society*).

All of these efforts will be for nought, of course, if there is insufficient fuel for these cells. Owing to its low density, hydrogen is difficult to transport efficiently and many hydrogen generation methods, such as splitting water by electrolysis, are slow and energy intensive. Indeed, some teams are working to remove hydrogen from the equation altogether, powering their fuel cells with petrol (*Applied Catalysis B: Environmental*) and ethanol (*Journal of Membrane Science*).

Researchers in China, however, have developed a method for the on-demand production of hydrogen from water, for supplying directly to a PEMFC (*Journal of Renewable and Sustainable Energy*). Their method involves using an alloy of gallium, indium, tin and bismuth to catalyze a hydrogen-generating reaction between water and an aluminum plate.

Splitting water via electrolysis may struggle with the on-demand production of hydrogen, but it could provide a solution to a significant issue associated with the production of electricity using renewable sources. Under the right conditions, wind and solar farms produce gluts of energy. Conversely, when the wind isn't blowing or the sun isn't shining, they produce nothing. By converting the excess energy generated by these sources into hydrogen during times of plenty, reserves of fuel are created that can be drawn on during times of want. »



Schematic illustration of the integrated solar flow battery. A perovskite/silicon tandem solar cell (in green) is hooked up to tanks of chemicals (in red and blue) that can store electricity for later use

WENJIE LI

Go with the flow

Another solution to this problem is the flow battery, which can be used to store truly massive quantities of energy. These hold electrical charge in tanks of positive and negative liquid electrolytes that are pumped through electrodes to generate electricity. After the charge is used up, the spent electrolytes return to holding tanks where they can be recharged. This process can be repeated over and over, and scaling-up the batteries so that they can store more energy simply requires constructing bigger tanks to store more electrolytes.

Flow batteries are not without their drawbacks, however. The majority, including an 800MWh behemoth now being built in China, employ toxic heavy-metal salts, such as vanadium dissolved in sulfuric acid, as electrolytes. Further, as demand for flow batteries increases, so too will the prices for these materials. Accordingly, much research has been undertaken this year into the development of economical and more environmentally friendly alternatives.

Flow batteries hold electrical charge in tanks of positive and negative liquid electrolytes that are pumped through electrodes to generate electricity

60°C

A new water-soluble polymer electrolyte can increase the working temperature of flow batteries to 60°C

Researchers in Austria, for instance, have developed an electrolyte based on vanillin, which can be extracted from vanilla pods (*Angewandte Chemie International Edition*). Researchers in the US are producing electrolytes using a plentiful and cheap by-product of the mining industry, iron sulfate, and a readily available organic material, anthraquinone disulfonic acid (*Journal of the Electrochemical Society*).

A team in Germany, meanwhile, has developed an electrolyte based on a water-soluble polymer. The German researchers claim that the adoption of this electrolyte would kill two birds with one stone. It would reduce reliance on heavy-metal salts and allow the maximum working temperature of flow batteries to increase from 40°C to 60°C, reducing the need for elaborate cooling systems (*Advanced Energy Materials*).

Other research teams are looking at ways in which flow batteries can be combined with energy-harvesting technologies to create the means to generate and store electricity in remote areas, which can be challenging to serve through conventional power grids. One such hybrid, comprising a flow battery charged by perovskite/silicon tandem solar cells, has been developed this year by an international team of researchers (*Nature Materials*, see image). ●

Free energy dream

The covid-19 pandemic has thrown up challenges and opportunities for Ravi Silva, as he works to turn his dream of ultra-cheap perovskite solar cells into reality

RAVI SILVA, director of the Advanced Technology Institute (ATI) at the University of Surrey in the UK, as well as head of its Nanoelectronics Centre, has a dream of everyone on the planet having access to free solar energy by 2035. He is determined that engineering will provide ultra-cheap solar cells that can be used anywhere.

25%
conversion efficiency of best-performing perovskite solar cells

"In one hour, the Sun provides enough energy to power the Earth for a whole year," Silva says. "We are not using it simply because we don't have engineering solutions to be able to capture that. My dream is that we will be able to produce electricity so cheaply that no-one will pay for it."

To turn this dream into reality, he, like many others, is turning to perovskite solar cells, which offer the potential of highly efficient conversion of sunlight into electricity and extremely low fabrication costs. Silva's work has already played a key role in boosting the conversion efficiency of perovskite cells to around 25%, which is as good as traditional silicon cells (Materials Today).

Unlike silicon, perovskites can be processed in solution, which means they can also potentially be used to produce flexible solar cells. The beauty of flexible systems is that they can be put on cheap substrates, such as plastics, says Silva. "Or you can have newspaper-type materials and print your solar cell on top of that."

Challenging the dream

Unfortunately, this dream is beset with challenges. "The biggest challenge is stability," says Silva. "One of the unfortunate things about perovskites is the fact that they oxidize easily." So if water vapor or oxygen get into a device, its performance will be affected.

He and his team are currently looking at different cover materials for perovskite solar cells, including materials used in commercially available organic light emitting diodes (OLEDs). "If we have the right cover materials then we can have perovskites last as long as we want," he predicts. These cover materials need to be cheap, compatible with existing systems and sustainable, he adds.

This year, his team also reported finding a way to improve the performance of perovskite solar cells by adding an internal layer of organic semiconductors made from fluorene-based conjugated polyelectrolytes (Nano Energy).

Another major challenge is that the best performing perovskite materials contain lead, which is toxic and can potentially leak out of the solar cells. One solution is to replace the lead with tin, which Silva and his colleagues have been investigating, but the reduced toxicity comes at a price.

"The unfortunate part is that the more tin you put into your solar cells, the less efficient they become, and that's also because of the way tin oxidizes," explains Silva. "So we need to still understand the material system better in order to stabilize the internal mechanisms. We also have to make sure that our packaging and encapsulation stops the permeation of water vapor or oxygen into the devices."

Open to opportunities

This year, a whole host of completely different challenges have been thrown up by the covid-19 pandemic. The first lockdown in the UK caused the labs at ATI to be closed for six weeks. After that, they only operated at 40% capacity, with researchers allocated two lab days per week, stretching to three in exceptional cases.

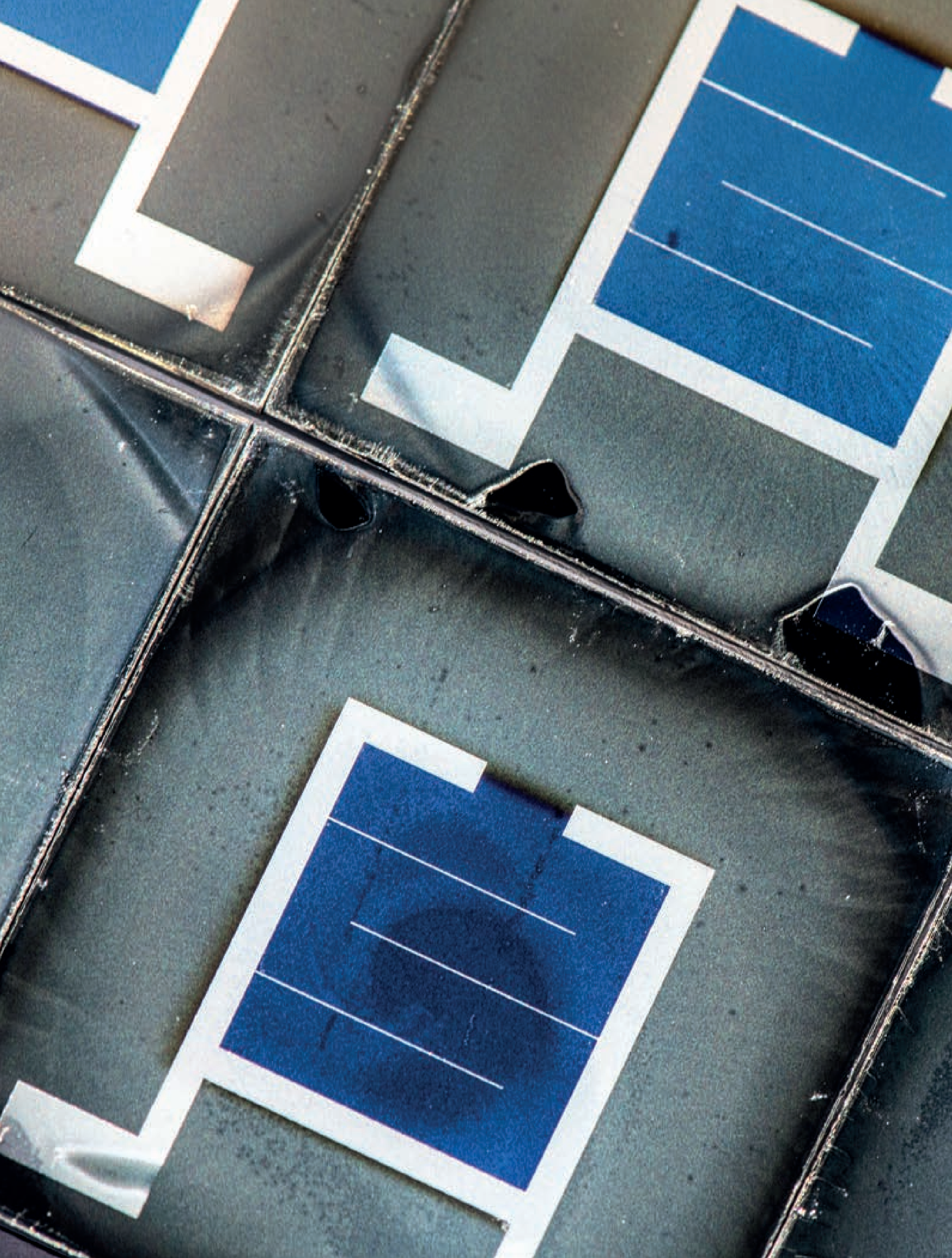
"In a sense it's good because people have to think much more carefully about what they need to do and what is time-critical," says Silva.

The members of his team have been working from home unless they need to go onto campus for teaching or face-to-face meetings. "The researchers themselves have done an amazing job working from home. It's not easy."

But the pandemic has thrown up opportunities as well. Silva and his team are contributing to an interdisciplinary project at the University of Surrey to create a cheap, wearable covid-19 detection system, with his team providing the electronics expertise. "Our electronic activities were redirected into looking into a new kind of sensor," he says. The tests work but their sensitivity still needs to be tweaked.

In addition, with more time to catch up on paperwork and write up research, the ATI actually won more funding contracts than normal in 2020.

But Silva misses the camaraderie and the chance meetings where technical problems can be aired and shared. He worries about providing sufficient support to his new PhD students and is also deeply concerned that funding for new PhDs has reduced significantly with covid-19. As well as reductions in government PhD funding, companies are also scaling back scholarship schemes for now. "I hope we are not losing a generation of PhD students," he says. ●



Developments in perovskite solar cells

In 2020, researchers were still hard at work trying to turn perovskite solar cells into a practical, commercial technology

Perovskite/silicon tandem solar cells

UNSURPRISINGLY, perhaps, the general theme for research this year on perovskite solar cells (PSCs) has simply been more of the same. Researchers have continued to explore a variety of approaches for enhancing the efficiency and stability of PSCs, while also trying to reduce their toxicity.

Perovskites are a class of semiconducting materials with a specific crystalline structure (ABX_3). Just over 10 years ago, scientists discovered that one class of perovskite, in which A is an organic cation, B is an inorganic cation and X is a halide anion such as iodide, bromide or chloride, makes a very effective light-absorbing material for use in solar cells. In particular, the perovskites methylammonium lead iodide ($CH_3NH_3PbI_3$) and formamidinium lead iodide ($FAPbI_3$) have proved to be star performers, responsible for PSCs that can convert around 25% of incident light into electricity. These conversion efficiencies rival those of conventional silicon solar cells.

In other respects, however, PSCs actually surpass silicon solar cells, hence the interest and excitement. For a start, they are cheaper to source and easier to produce. Whereas silicon solar cells need to be fabricated at high temperatures and under vacuum conditions, perovskite solar cells can be processed in solution at low temperatures, significantly reducing manufacturing costs and raising the possibility of simply printing them onto surfaces. They are also flexible and lightweight compared to the heavy and rigid silicon-based cells.

Perovskite mineral

The challenge is to transform all this interest and excitement into a practical, commercial technology, which is what researchers have continued to work on in 2020. For a start, the 25% efficiencies have so far only been achieved in small-scale PSCs, with efficiency levels plummeting as the size of the solar cell increases. This is due to surface imperfections that arise from »

DENNIS SCHROEDER/NREL

the solution-processing techniques used to crystallize perovskites. These techniques can leave behind contaminants such as oxygen and amorphous carbon, and produce defects, including some that cause 'deep traps'. These are areas where energized charge carriers, meaning negatively charged electrons and positively charged 'holes', get stuck and recombine, generating heat rather than electricity.

As the size of the cells increases so does the number of contaminants and defects, reducing the amount of solar power generated. That's why significant research efforts are aimed at developing better fabrication techniques and producing higher quality materials with fewer defects.

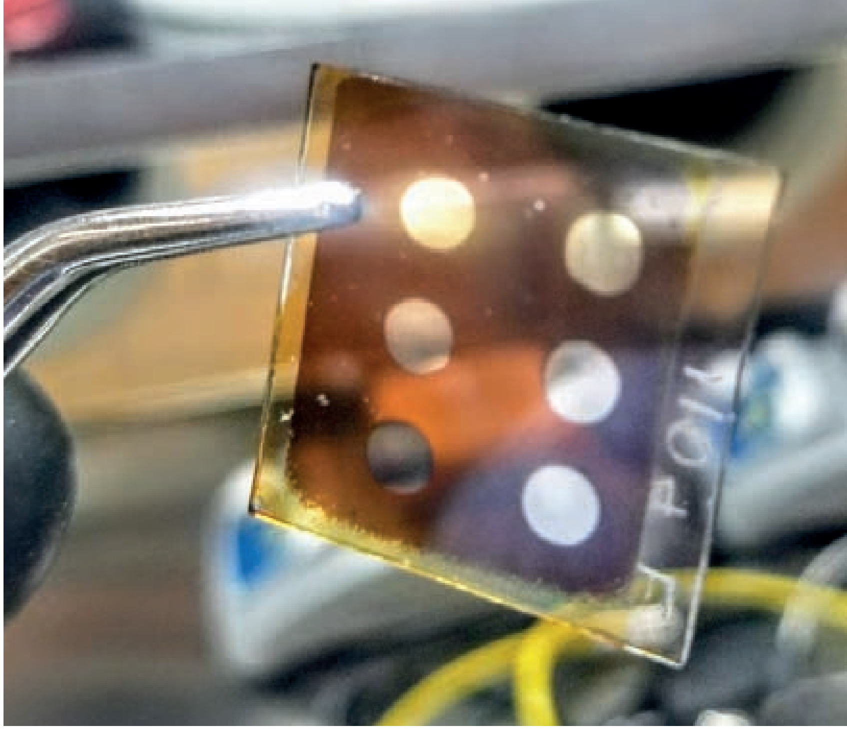
Dealing with defects

One way to prevent defects from forming is to chemically modify the perovskite film or tweak the composition of the precursor solution to optimize thin film and crystal formation. In July, a Japanese team reported that adding a potassium salt between perovskite layers in the PSC 'healed' tiny defects on the perovskite surface (*Nature Energy*). The researchers also discovered that adding another perovskite material between the layers prevented cracks forming on the surface and stopped moisture from entering.

A research group from Saudi Arabia devised a post-crystallization treatment method that appears to remove surface and bulk defects generated during crystal growth (*PLOS One*). Their method uses bromine vapors to penetrate the cells and reach the deep-lying layers, and appears to boost electrical conductivity and carrier mobility.

One of the difficulties with preventing the formation of 'deep traps' is that scientists don't really understand what kind of defects produce them. But by studying PSCs with photoemission electron microscopy, an international team of scientists was able to discover that deep traps only form at junctions where an area of the perovskite material with a slightly distorted structure meets an area with a pristine structure (*Nature*).

These different areas occur in polycrystalline perovskite films, made up of lots of different crystal grains. Thus, another way to improve the efficiency of PSCs is to replace polycrystalline perovskite films with single-crystal films, comprising one large crystal grain, as single crystals have fewer defects. In July, researchers from the US and China reported a new a method, based on semiconductor fabrication processes, for creating single-crystal perovskite films with controlled area, thickness and composition (*Nature*, see photo). These films have fewer defects, greater efficiency and enhanced stability compared to their polycrystalline counterparts.



HARSHAVARDHAN GAONKAR

The caesium-containing PSC developed by researchers in the US.

Commercial solar cells need to be able to withstand years of operation, often while exposed to the elements, but PSCs quickly degrade on exposure to sunlight, high temperatures and moisture

Shedding sunlight on stability

Stability, or lack of, is another perennial challenge that researchers have continued to work on in 2020. Commercial solar cells need to be able to withstand years of operation, often while exposed to the elements, but PSCs quickly degrade on exposure to sunlight, high temperatures and moisture, making them of little practical use at the moment. Fortunately, there are a wide range of possible options for enhancing their stability.

One option involves changing the compositions or dimensions of the perovskite material. For example, light impairs PSCs by disrupting the carefully arranged composition of elements within the perovskite material, known as light-induced phase-segregation. In March, a US research group reported that PSCs containing three halides (chlorine, bromine and iodine) could suppress this light-induced phase-segregation, even at an illumination of 100 suns, while retaining a relatively high conversion efficiency of 20.3% (*Science*).

Another option is to add protective molecules to the perovskite material. Researchers from the US and China found that adding a bulky molecule called bithiophenylethylammonium to the surface of a perovskite stabilizes the movement of ions, preventing chemical bonds from breaking easily (*Nature*). As a consequence, this perovskite material was able to withstand temperatures of 100°C.

Despite its high conversion efficiencies, methylammonium lead iodide is particularly unstable, which may be due to the volatile nature of the organic cation. To correct this problem, researchers are attempting to replace the organic methylammonium with inorganic caesium, which is significantly less volatile. For example, researchers in the US reported using caesium to produce a perovskite material that showed no thermal degradation even at very high temperatures for over three days, although its conversion efficiency was low, at 11.8% (ACS Applied Energy Materials, see photo).

Lead-free perovskites

Researchers have also continued to explore ways to remove the lead from PSCs, while retaining high conversion efficiencies, because lead is toxic and could potentially leak out of PSCs. The most straightforward option is to replace the lead with less toxic elements, such as tin, which should theoretically produce a perovskite with excellent optical properties. In practice, however, tin-containing PSCs such as formamidinium tin iodide ($FASnI_3$) have displayed only mediocre conversion efficiencies and age rapidly. The tin cations in the perovskite react quickly with oxygen in the environment, reducing the conversion efficiency.

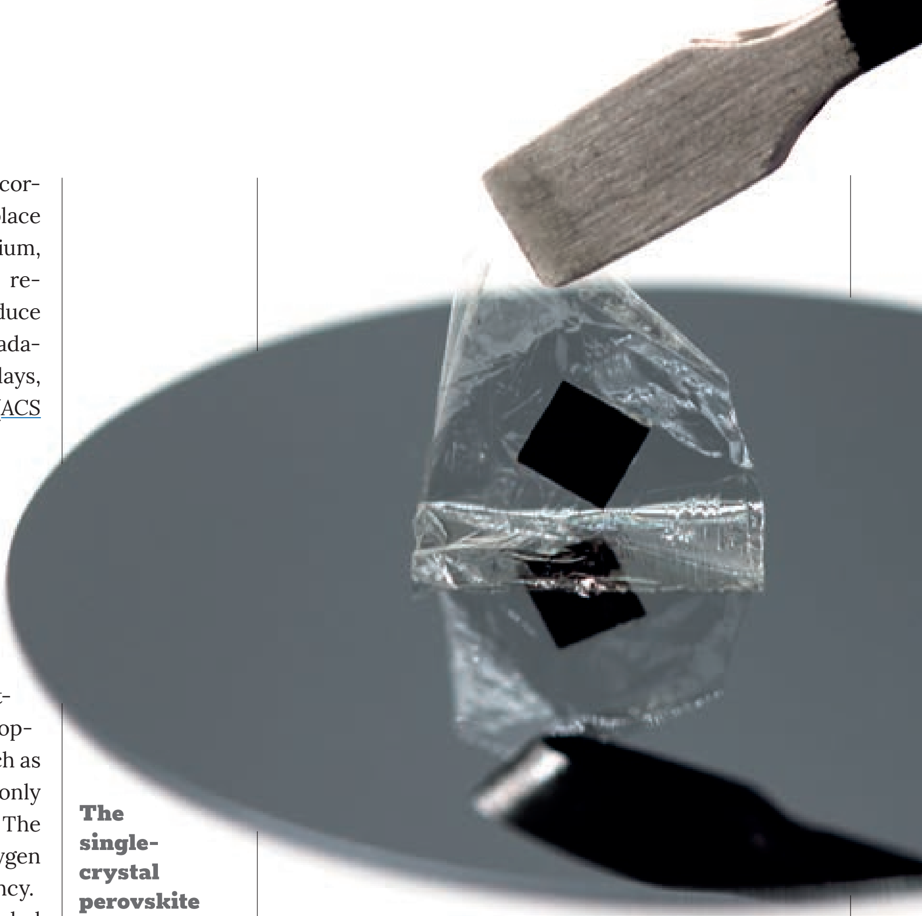
In May, however, an international collaboration led by German and Chinese researchers reported developing a formamidinium tin iodide PSC that performed well over long periods (ACS Energy Letters). The researchers did this by inserting organic groups (phenylethylammonium chloride) into the perovskite; these groups formed a barrier that prevented the tin cations from oxidizing. A similar approach was taken by a team of Dutch scientists, who mixed formamidinium tin iodide crystals with layered materials containing phenylethylammonium to produce a more stable material (Advanced Functional Materials).

Other researchers are looking to replace the lead with barium. For example, researchers from the US and India developed a lead-free chalcogenide perovskite (barium zirconium sulphide), which they say is intrinsically more stable and water-resistant (Advanced Functional Materials). It's also highly resistant to breaking down when exposed to moisture or intense sunlight.

Rather than replace the lead, some researchers are trying to prevent it from leaking out. Researchers in the US have done this by applying lead-absorbing films to the front and back of a PSC (Nature), while a Korean research team has developed novel polymers for capturing the leaking lead (Advanced Energy Materials).

Power in tandem

Some of these problems with efficiency and stability could also be addressed by combining PSCs with silicon solar cells to produce so-called tandem cells, which researchers have continued to investigate in 2020. Because PSCs and silicon solar cells tend to absorb light most effectively at slightly different wavelengths (PSCs prefer shorter, bluer wavelengths, while silicon solar cells prefer longer, redder wavelengths), a tandem cell can absorb a greater range of wavelengths.



The single-crystal perovskite thin film developed by researchers from the US and China.

YUSHENG LEI

***So called tandem cells could achieve conversion efficiencies of up to* 44%**

This could theoretically allow tandem cells to achieve conversion efficiencies of up to 44%. The more robust silicon solar cells could also help to protect the more sensitive PSCs from the damaging effects of light and moisture. As a demonstration, a team of researchers from the US and Korea produced a tandem cell with a conversion efficiency of almost 27%, compared with 21% for the PSC on its own, and the team is confident it can get that efficiency to over 30% (Science).

But tandem cells have a key limitation. The silicon wafers used for solar cells have an uneven surface, making it difficult to coat a uniform layer of perovskites on top. So far, most tandem cells have been made by first polishing the silicon surface to make it smooth, which is costly, and then adding the perovskite layer.

Researchers from Canada and Saudi Arabia have come up with a cheaper alternative, which doesn't require any modifications to the silicon. They mixed perovskites with liquid to create a 'solar ink' that can be printed on silicon surfaces and increases the thickness of the perovskite layer. The resulting tandem cells achieved an efficiency of 25.7% and were also stable (Science).

Despite all these promising developments, the work to turn perovskites into a practical, commercial solar power technology looks set to continue in 2021. ●

Raising the temperature

Not only did Zhifeng Ren and his group not let the pandemic stop them working, but they even developed a technology to help control its spread

FOR ZHIFENG REN, professor of physics at the University of Houston, US, the pandemic and associated disruption has been an inconvenience, but it hasn't stopped him and his group from working on their research projects. Indeed, it even led them to start working on an entirely new research project.

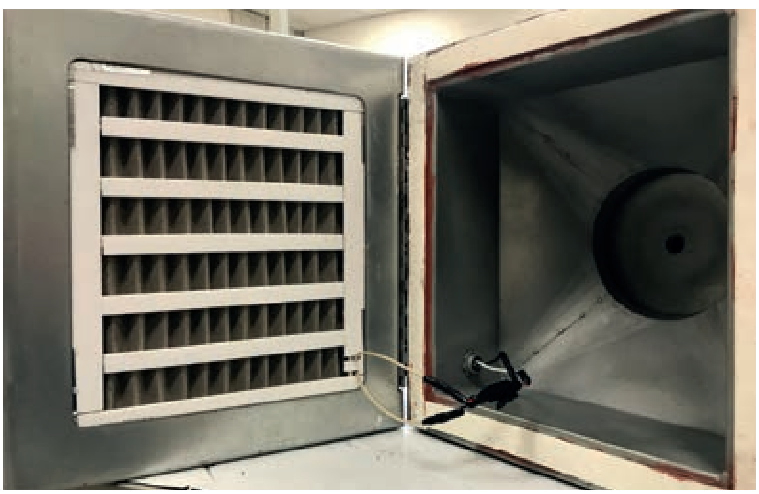
"I have never closed the labs," says Ren. "All those research projects have not been stopped. They've been affected to some extent, but they've never been stopped."

He's managed to keep going by adopting various precautionary measures, such as ensuring his group members only come into the lab to conduct experiments, while doing any analysis and write-ups at home, and always wearing masks. "Masks are very, very important," he says. "They wear masks all the time."

With these measures in place, he and his group have continued working on their four existing research projects throughout 2020. Two of these projects involve developing novel materials with useful thermal properties, meaning thermoelectric materials and materials with a high thermal conductivity.

Thermal properties

Thermoelectric materials are able to convert a heat difference across them into an electric current. Ren and his group are developing such materials for power generation applications, allowing electricity to be generated from the waste heat produced by sources such as power stations and cars. They are focusing on zirconium-based semiconducting compounds for this purpose, which they dope with metallic elements such as vanadium, niobium and tantalum to enhance their thermoelectric properties (*Materials Today Physics*).



The nickel foam anti-viral filter developed by Ren and his group.

UNIVERSITY OF HOUSTON, COLLEGE OF NATURAL SCIENCES & MATHEMATICS

Materials with a high thermal conductivity are useful for managing heat in electrical devices by transporting it away from heat-sensitive areas. Diamond has the highest known thermal conductivity, but manufacturing synthetic diamond is difficult and costly, and so researchers are searching for alternatives.

Ren and his group are investigating boron-based materials such as boron arsenide and cubic boron nitride, which have both shown much promise (Science). "We're hopeful we can get close to the thermal conductivity of diamond," says Ren, "but we're not there yet."

They are also developing nanoparticles for oil production. At the moment, heavy oil is extracted from the ground by injecting steam to reduce the oil's viscosity, but producing this steam requires a lot of energy. Ren and his group are looking to replace the steam with nanoparticle systems.

In recent work, they showed that injecting sodium nanoparticles into heavy oil followed by water can make

the oil much easier to extract. This is because the sodium nanoparticles react with the water to produce sodium hydroxide, hydrogen gas and heat, all of which help to reduce the oil's viscosity. (Materials Today Physics). According to Ren, the University of Houston is currently in discussions with companies about commercializing this nanoparticle system for the extraction of heavy oils.

200° *is sufficient to kill the trapped* SARS-CoV-2

Nickel foam

Finally, they are working on developing novel catalysts for splitting water to produce hydrogen. Specifically, they are developing catalysts for splitting seawater, which is more challenging than splitting fresh water because of the minerals in seawater. To operate efficiently, this process also ideally requires two catalysts, one for producing oxygen and one for producing hydrogen.

Ren and his team are developing nickel-based catalysts for this purpose. Recently, they showed that a catalyst comprising nickel molybdenum nitride nanorods covered with nickel iron nitride nanoparticles supported on a nickel foam, for releasing oxygen, together with the nanorods on their own, for releasing hydrogen, can efficiently split seawater (Nature Communications).

This work with nickel foam led neatly into their new research project, which involves developing a filter for killing the SARS-CoV-2 virus responsible for covid-19

This work with nickel foam led neatly into their new research project, which involves developing a filter for killing the SARS-CoV-2 virus responsible for covid-19. Because nickel foam is porous, it can trap viruses in its pores. And because it's electrically conductive, applying an electric current causes the foam to heat up to around 200°C, which is sufficient to kill the trapped viruses. The idea is therefore to attach these nickel foam filters to air conditioning systems to prevent the spread of the virus inside buildings (Materials Today Physics).

Ren and his team began work on this project just as the pandemic started to ramp up in the US. "I got the first email asking for assistance on March 31st," he says. By June, he and his team had developed the filter and shown that it could kill 99.8% of viruses passing through it. Now it is being deployed as mobile units and in air conditioning systems throughout the US, especially in schools, and the rest of the world by the US company Integrated Viral Protection (IVP).

"Up to now, IVP have deployed hundreds of mobile units," says Ren. "In the next few months, there will probably be close to a thousand units being deployed domestically and internationally, and many more next year." ●

UNIVERSITY OF ROCHESTER PHOTO/J. ADAM FENSTER

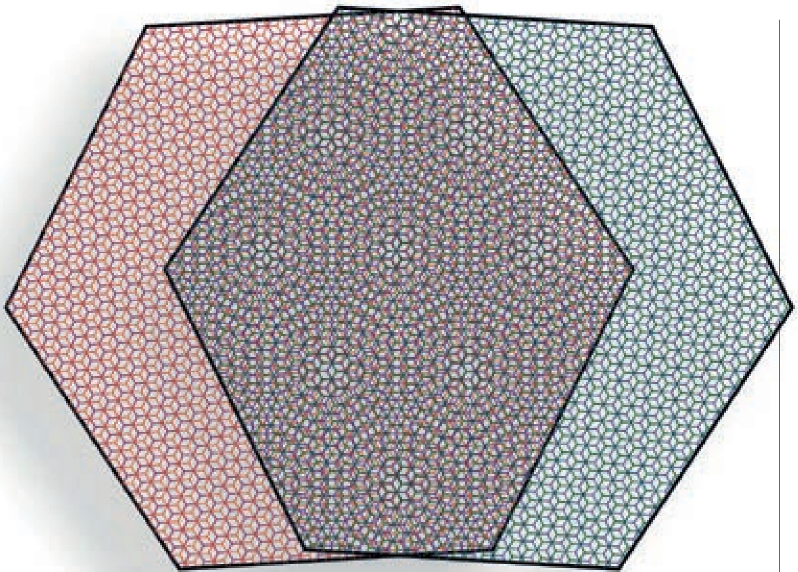
Developments in quantum materials

Breakthroughs in quantum materials this year, including the creation of room-temperature superconductors and the quietest qubits, brought the long-heralded quantum future closer than ever before

SCIENTISTS HAVE long been striving to perfect their ability to develop quantum materials for various applications, from quantum computing to transporting electrical power without loss. These quantum materials come in many different forms, but they all take advantage of the bizarre quantum properties of subatomic and elementary particles such as electrons and photons.

This work is now beginning to bear fruit. Over the past year, scientists have enjoyed several major successes and breakthroughs, suggesting that the quantum future is almost here.

Take quantum computing. By utilizing quantum entities that can exist in a 'superposition' of states, quantum computing replaces the classic bits of conventional computing, which can be either one or zero, with quantum bits, or qubits, that can be both one and zero at the same time.



RIGHT
Illustration of the moiré pattern produced by twisting two sheets of bilayer graphene

LEFT
A magnet floats above a superconductor cooled with liquid nitrogen

MATTHEW YANKOWITZ/UNIVERSITY OF WASHINGTON

Quantum computers offer the promise of performing calculations that conventional computers find almost impossible. As an early demonstration, Google announced in April that its Sycamore quantum processor – with 53 qubits – had succeeded in verifying that a set of numbers was randomly distributed in just 200 seconds. The same calculation would have taken the world's most powerful classic supercomputer around 10,000 years. But even though simple quantum computers do now exist, scientists are still hard at work developing materials for the next generation of more powerful devices.

In August, Australian scientists reported creating the quietest qubits ever designed (Advanced Materials). Not that quantum computers are loud, but sometimes the signals they generate are hazy. Imperfections in quantum materials can cause charge noise – like bad radio signals – that interferes with the pristine accuracy of quantum information. To overcome this, the Australian team designed an optimized fabrication process for utilizing electron spins as qubits in extremely pure crystalline silicon, allowing them to achieve a noise level 10 times lower than previously recorded.

An Australian team lowered the qubit charge noise level by a factor of
10

As well as hosting qubits, quantum computers also need to be able to read them. To this end, researchers in Finland developed a new bolometer – a sensor that measures incident radiation from the heat it generates – capable of determining quantum energy with unprecedented resolution (Nature).

Until now, the best qubit-reading technology was based on detecting changes in voltage, but this relies on bulky machinery and excessive power consumption. Moreover, it introduces noise and read-out errors. The new bolometers – based on the unique properties of graphene – should overcome these complications. They are 100 times faster than their predecessors, which are based on gold-palladium mixtures, but retain the same reduced noise levels.

Japanese researchers broke yet another record in quantum technology, by increasing the length of time of qubits can hold information by a factor of 10,000 (Nature Materials). To accomplish this, the researchers used a charged particle known as an electron hole – technically, the absence of an electron – as a qubit, which they trapped by implanting a boron atom into a silicon crystal. This hole was then able to encode information through a combination of spin and orbital motion, allowing it to retain the information for longer.

New light on quantum materials

Quantum technologies will also allow faster processing speeds, swifter flows of information and more secure communications networks. But all these new advances » will require new materials and devices capable of withstanding the needs of the quantum revolution. Throughout the past year, researchers have been working hard to produce such materials and devices.

For example, a team led by US researchers pioneered the design of a new source of single photons that can be easily controlled using electric fields (Science Advances). Photons – light particles – can be used to encode and transmit information in quantum devices. However, most tools for generating single photons are either imprecise or unstable.

This new design solves these problems by using a 2D semiconductor – tungsten disulfide – with carefully engineered defects that produce single photons when a voltage is applied. By tailoring this voltage, the researchers managed to adjust the physical properties of the photon – such as wavelength and orientation – with extraordinary precision. This raises the possibility of generating truly identical photons at will, which could be used to send information across quantum processors, and potentially lead to a future 'quantum internet' – a network connecting quantum computers around the globe.

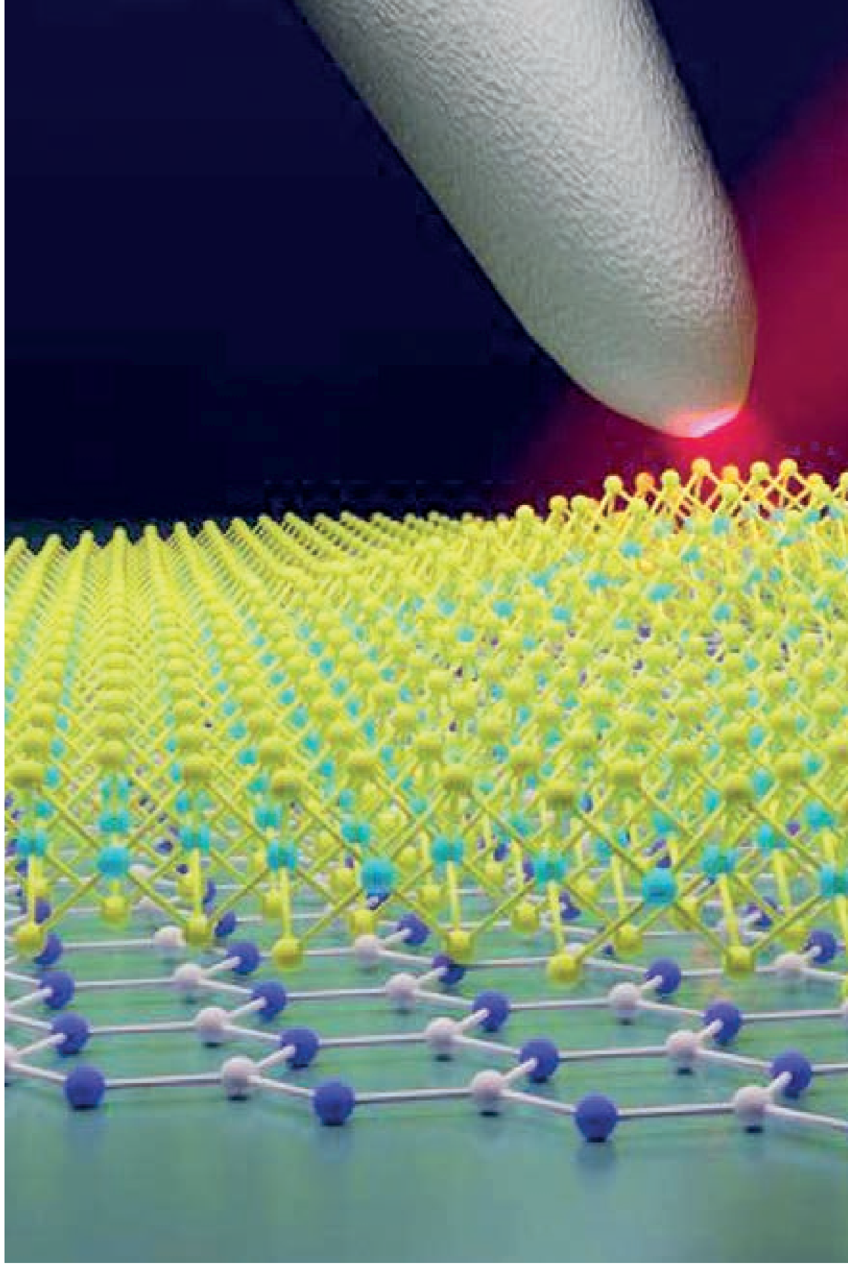
Meanwhile, a multidisciplinary team from Germany, Japan and the US explored the potential of a related 2D material for emitting single photons (Nature Nanotechnology see image). Earlier this year, they showed that the strain generated by 'nanobubbles' – small pockets of fluids – in ultrathin layers of tungsten diselenide can stimulate the emission of single photons at specific wavelengths.

A family affair

Two families of materials that show particular promise for use in quantum technologies are topological insulators and 'twisted' 2D materials.

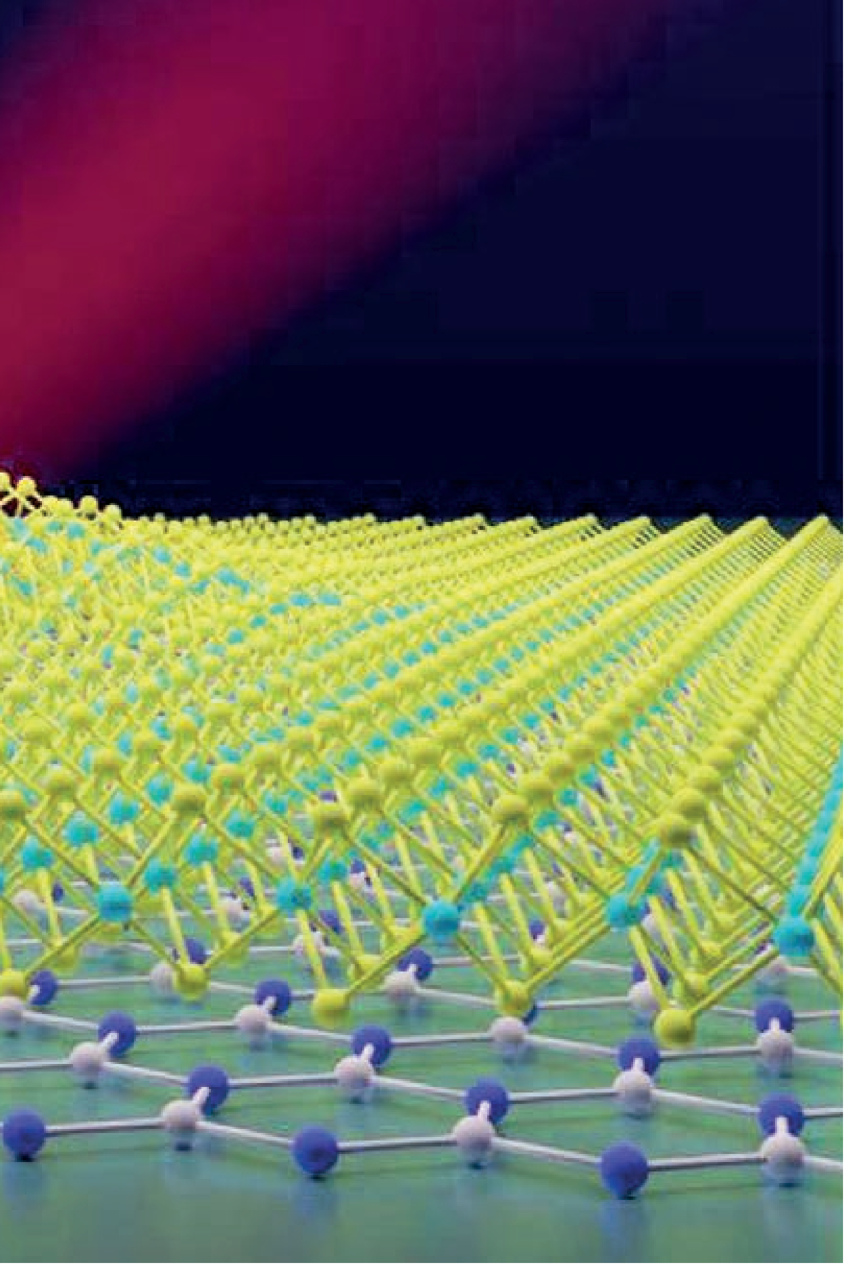
Topological insulators are like a cake wrapped in tin foil – materials with a conductive surface and an insulating interior. Because some topological insulators conduct current without energy loses, they could find similar applications to superconductors, as well as provide a new platform for flawless quantum computing (Nature Physics). This year, research in topological materials led to the discovery of the first room-temperature topological magnet, which exhibits exotic quantum effects that could provide higher data storage capacities and allow greener computing technologies (Nature).

Two families of materials that show particular promise for use in quantum technologies are topological insulators and `twisted' 2D materials



Since the discovery of the 'magic angle' in graphene, twisted bilayer 2D materials have attracted lots of attention, leading to the field of 'twistronics'. Misaligned graphene sheets display moiré patterns – like the blur created by houndstooth jackets on TV – which can confer exotic properties, including superconductivity (see image). This only happens at specific angles of misalignment, however, hence the term 'magic angle'.

In 2020, researchers expanded the range of properties that can be produced by misaligned graphene sheets. One group found that, at certain angles, misaligned graphene sheets can interact with mid-infrared light, the kind of radiation humans detect as heat (Nature Photonics). This effect could be useful in many applications, from autonomous vehicles to more efficient solar panels. Another group found that the misaligned sheets can unlock an unusual form of magnetism, generated by the collective swirling motion of electrons (Nature Physics).



Schematic of a laser-illuminated nano-optical probe investigating a strained nanobubble of tungsten diselenide

NICHOLAS BORYS/MONTANA STATE UNIVERSITY

Nevertheless, it is the superconducting properties of magic-angle graphene that are still generating most interest. Not so much because magic-angle graphene could become a useful superconductor in its own right, as the trait only appears at temperatures of a few degrees above absolute zero, but because it might offer a useful way to explore unconventional forms of superconductivity.

Such unconventional forms are thought to be responsible for high-temperature superconductors like cuprates, which are superconducting at temperatures of around 100K (-173°C), as well as the superconductivity of magic-angle graphene. But cuprates are complex, copper oxide materials that are difficult to model, whereas two sheets of graphite, made up solely of carbon atoms, are much simpler systems.

Already, scientists have uncovered evidence that the superconductivity in magic-angle graphene is due to the moiré pattern causing the electrons in the two sheets to lose their kinetic energy, thus slowing them down enough so they can start interacting. In one recent study, researchers in the US and Japan spotted the electrons in magic-angle graphene displaying highly collective behavior, all doing the same thing – or displaying the same properties – at the same time, like a flock of birds (Nature Physics).

Room for superconductors

The undoubted highlight of superconducting research in 2020 was the achievement of room-temperature superconductivity – albeit at ultra-high-pressures. The quest for room temperature superconductors has been, for a long time, a holy grail of physics. Such a discovery would allow the transmission of electrical energy without loss and the creation of super magnets – for MRIs and maglev trains – that do not require cooling.

This achievement came from the recent discovery that materials combining hydrogen with rare-earth elements can superconduct at record-breaking temperatures. In February, an international team of researchers reported that lanthanum superhydride could superconduct at the temperature of a home freezer (Nature). This is due to atomic quantum fluctuations that glue the symmetric structure of this lanthanum compound, providing the ideal conditions for electrons to travel without resistance.

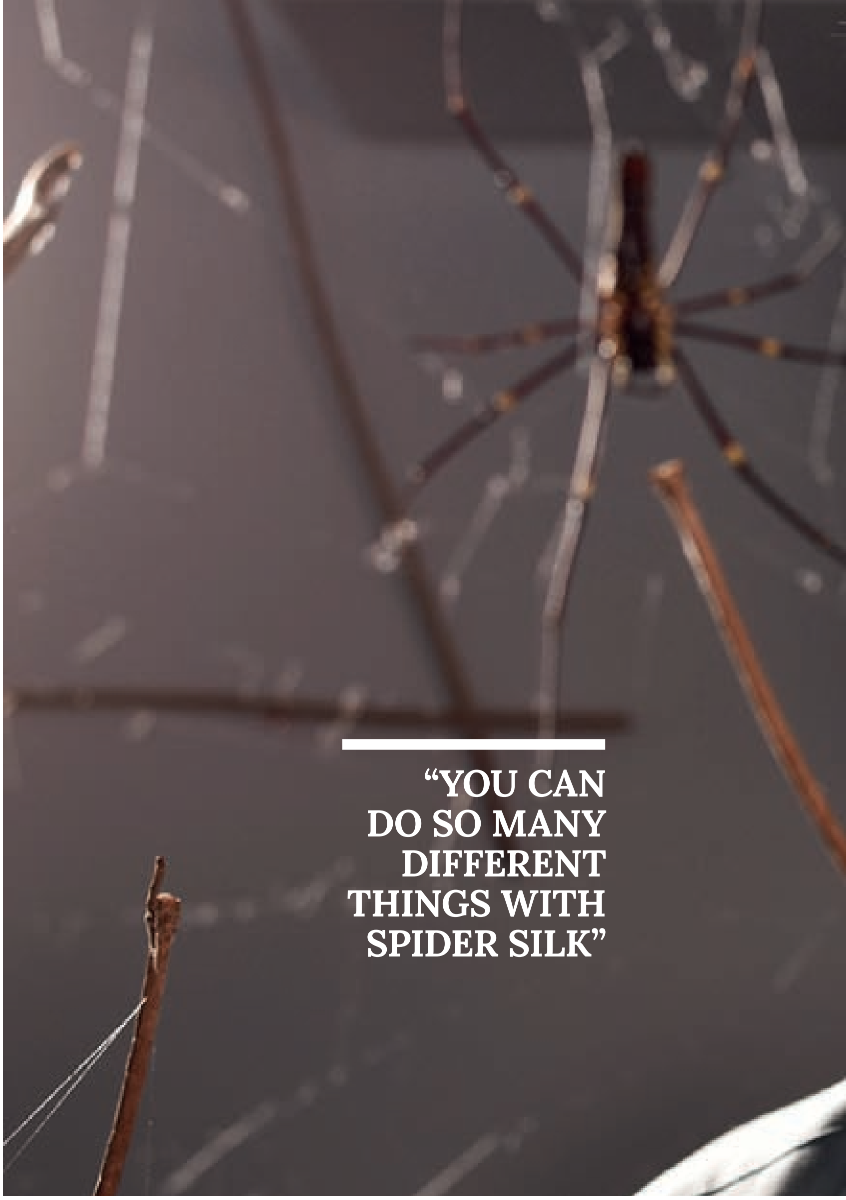
Then, in October, US researchers reported that yttrium superhydride exhibited superconductivity at -11°C. Even more astonishingly, they showed that a mixture of hydrogen, sulfur and carbon, known as carbonaceous sulfur hydride, became superconducting at a balmy 15°C (Nature). The catch was this required a pressure of 39 million psi, or around 1.55 million times atmospheric pressure, created with super-strong diamond anvils. Another problem is that the researchers only produced a few picolitres of the material. But they are confident that further chemical tweaks will lead to versions that work at lower pressures, making them easier to synthesize in larger amounts.

Researchers also explored various other superconducting options in 2020. For example, they continued to investigate nickelates, which are essentially nickel-based versions of cuprates. In 2019, US researchers discovered the first nickelate able to superconduct, at temperatures of around 10K (-263°C), but other teams struggled to replicate their findings. This year, researchers from China, Austria and Germany showed this is because hydrogen can easily become incorporated into nickelates during their synthesis, altering their electrical behavior and stopping them from superconducting (Physical Review Letters). Their finding was confirmed by a team from Singapore, which managed to produce a superconducting nickelate by ensuring hydrogen was excluded (Physical Review Letters).

Similar successes and breakthroughs in 2021 should bring the quantum future even closer.

Touch of luck

Thanks to a lucky combination of circumstances, Thomas Scheibel has both been able to keep his labs open throughout the pandemic and apply his research to the fight against SARS-CoV-2



UNLIKE MATERIALS scientists in many other countries, Thomas Scheibel, professor of biomaterials at the University of Bayreuth in Germany, has not suffered too much disruption from the covid-19 pandemic. "We never had a lockdown of the labs," he says.

This was in part due to Germany having more success than other countries in keeping the pandemic under control and in part due to Bavaria, the region of Germany where the University of Bayreuth is located, deciding to keep its universities open. But it was also assisted by the fact that Scheibel's Department of Biomaterials had just moved into a brand-new building with wide corridors and expansive laboratories that were perfectly suited to social distancing. Together with implementing measures such as wearing face masks, this has allowed Scheibel and his group to continue their research without interruption.

"I think it's a very, very lucky combination of things that happened in my special case," Scheibel says.

Spider silk

Also lucky was the fact that Scheibel's existing research could easily be co-opted into the battle against the SARS-CoV-2 virus that causes covid-19. Much of this research revolves around spider silk, which Scheibel and his group are developing for a wide range of applications.

"You can do so many different things with spider silk. We can make air filters for vacuum cleaners and face masks. Then, at the same time, it can be implanted into the body to make a scaffold for growing new tissue. Same molecule, different processing technologies, different applications."

Scheibel's Department of Biomaterials had just moved into a brand-new building with wide corridors and expansive laboratories that were perfectly suited to social distancing

One of the amazing things about spider silk is that microbes don't grow on it, even though it's made from just the kind of amino acids they usually like to consume. Scheibel and his group helped show this is mainly due to the physical structure of the spider silk preventing the microbes from binding, rather than to any kind of chemical anti-microbial effect. They then went on to produce 2D films and 3D hydrogels from several of the proteins in spider silk and demonstrate that these materials could actively repel various pathogenic bacteria and fungi (*Materials Today*).

If Scheibel and his group also added a cell-binding motif to these materials, then they would bind mammalian cells while still repelling bacteria and fungi. This means they could make ideal scaffolds inside the body, allowing body cells to grow on them while repelling any microbes; other potential uses include helping to keep food fresh and preventing the formation of biofilms on surfaces. And as luck would have it, there's a good chance these materials could be just as effective at repelling viruses as they are at repelling microbes.

Pure antibodies

This is the idea behind a new EU project that Scheibel and his group have just started working on: "We were very lucky to have a big EU proposal granted to develop materials for purifying biopharmaceuticals, especially antibodies." Therapeutic antibodies are usually produced by genetically engineered mammalian cells in huge bioreactors, but this means the antibodies often become contaminated, including by the many viruses that infect mammalian cells. These contaminants obviously need to be separated from the antibodies before they can be used as a treatment.

Scheibel and his group are looking to develop novel materials based on fiber-forming proteins, including spider silk proteins, for doing this. "The proteins are modified in a way that gives them the ability to specifically bind to bio-functional groups or biologicals such as antibodies," Scheibel explains.

Originally, the main focus of the project was on purifying antibodies that target adenoviruses, but the covid-19 pandemic has broadened the scope to encompass antibodies that target coronaviruses as well. "We switched the program slightly and now this is part of our project," says Scheibel. "We could immediately adapt to the new situation."

12

years on, Scheibel's biotech company is still going strong

The project is still in its early stages, but has so far gone well. The idea is to commercialize any materials that are developed, but Scheibel has experience in this area, as he founded a biotechnology company 12 years ago that is still going strong.

To go from initial research to commercialization requires a wide range of different skills and abilities, but they can all be found in Scheibel's group. "My lab is multidisciplinary," he says. "We do pretty much everything, from biology, molecules, processing, simulation of the molecules, simulation of the processing, towards application." Recently, his group even helped discover a new species of orb-weaving spider in Colombia, which they named *Ocrepeira klamt* (PLOS One).

With luck, Scheibel and his group will be able to continue doing everything for the foreseeable future. ●

Developments in biomaterials

From disposable nappies and optical fibers to superglue and bone repair, biomaterials researchers have been nothing if not ambitious in 2020

THE STORY OF biomaterials in 2020 was one of continued expansion, both in terms of the range of biomaterials being developed and the range of applications they were being developed for.

In bioplastics, researchers got ever more creative as they investigated the potential of some rather unlikely natural feedstocks. For example, researchers from Sweden managed to produce disposable nappies from wheat gluten, by chemically modifying the gluten to enhance its swelling potential (*Advanced Sustainable Systems*).

Others continued working with tried-and-tested feedstocks such as the microscopic aquatic plants known as algae, but found novel uses for them. A team of US researchers developed a method for converting algae oil into biodegradable polyurethane foams, which they used to produce shoe soles and the foot-bed of flip-flops (*Bioresource Technology Reports*), and mattresses and yoga mats (*Green Chemistry*).

Meanwhile, Brazilian researchers made an optical fiber out of agar, a natural gelatin obtained by boiling algae (*Scientific Reports*, see photo). The fiber contains six 0.5mm cylindrical airholes around a solid core. Because the refraction indices of the agar core and the airholes differ, light becomes trapped within the fiber. The researchers speculate it could be used for *in vivo* imaging and phototherapy.

Seaweed and spiders

Keeping with the aquatic theme, researchers from Finland and Brazil combined chitin nanoparticles extracted from blue crab shells with alginate, a compound found in seaweed, to make a new kind of strong, antimicrobial fiber (*ACS Sustainable Chemistry and Engineering*). This fiber shows potential for use as surgical thread, and in wound healing and burn treatments.

Spider silk is another tried-and-tested substance that has attracted the attention of material scientists for years. Its strength and ultra-lightness makes it suitable for tear-resistant clothing, automobile and aerospace components, drug delivery systems, implant devices, and scaffolds for tissue engineering. But getting enough of the protein is difficult because only a small amount can be produced by each spider, and so researchers are working on finding ways to produce artificial spider silk. Japanese researchers, for example, have shown how photosynthetic bacteria that grow in seawater can be genetically engineered to produce a key silk protein from the golden silk spider (*Communications Biology*).

Golden silk spider (Nephila clavipes)

The fiber contains six 0.5mm cylindrical airholes around a solid core

½mm

As a major component of plant cell walls, there's no such difficulty getting hold of lignin. Indeed, the problem has been finding enough uses for lignin, which is a major waste product of paper manufacture. Traditionally, this waste lignin has mainly been burnt, but scientists are trying to find better uses for it. A team in the US, for example, treated purified lignin with potassium permanganate, coated the mixture onto an aluminium plate to form a 'green' electrode and then used it to assemble a supercapacitor (*Energy Storage*).

As usual, though, researchers have been paying even more attention to another major component of plant cell walls: cellulose. In particular, they are busy developing novel materials from tiny cellulose nanofibrils. Advantages of these nanofibrils, also known as nanocellulose, include chemical inertness, excellent stiffness, high strength and low density, and they can be employed in many applications, such as nanocomposites, biomedical products, food coatings and many more.

Cellulose nanofibrils

A key driving force in research into nanocellulose-based materials is the search for novel applications. This year, Swiss researchers combined cellulose nanofibers with silver nanowires and 2D materials known as MXenes to create ultra-light, flexible, durable materials that are extremely good at blocking electromagnetic radiation, which could be used to shield electronic components from electromagnetic fields (*Advanced Science*, see photo). »

RIKEN

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Electromagnetic shielding material made from a composite of cellulose nanofibrils and silver nanowires

The strong adhesive properties of nanocelluloses means they also show promise as binding components. For example, a recent study looked at colloidal assemblies of particles, which show potential in applications such as catalysis and sensing. Scaling up these assemblies into cohesive bulk materials remains challenging, however, as getting the particles to stick together can prove difficult. Now, a team of Finnish and Brazilian researchers has shown that cellulose nanofibrils can be added to virtually any particle to produce robust superstructures at scale (*Science Advances*).

Another promising application for nanocellulose is super-glue. A team of Japanese, Chinese and Canadian researchers has designed an 'eco-glue' from cellulose nanocrystals (*Advanced Materials*). Just a few drops of this eco-glue can hold up to 90kg in weight, they claim. The simple production method involves adding water to the nanocrystals (sourced from recycled paper or the agroindustry), saving time and money compared with usual processes for making high-strength glues.

Advantages of cellulose nanofibrils include chemical inertness, excellent stiffness, high strength and low density

Cellulose nanofibrils comprise molecular chains that align in one direction, and each chain has different optical properties depending on the direction it is aligned, which makes them ideal for optical fibers. Japanese researchers have designed a liquid-phase fabrication method for producing nanocellulose films with several axes of alignment, allowing them to programme the direction of patterns (*Nanomaterials*). Using 3D-printing methods for increased control, this work may lead to cheaper and more environmentally friendly optical devices.

Other researchers are also combining cellulose with 3D printing. But while it's straightforward to make cellulose 'ink' (just add water), the challenge has been to produce solid objects with high cellulose content and complexity. Now, Swiss researchers claim they've found a way to print objects of almost unlimited complexity with high levels of cellulose particles (*Advanced Functional Materials*). After printing with an ink containing 6–14% by volume of cellulose, the team used a densification process to increase the cellulose content of the printed object to a volume fraction of 27%.

Printing bio-inks

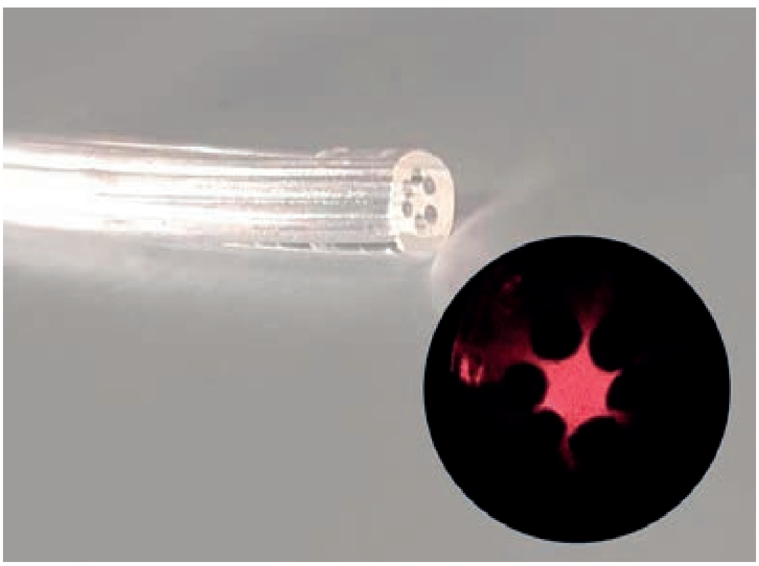
Various other biomaterials are also being developed as 'bio-inks' for 3D printing. Lithuanian researchers have designed a bio-ink made from soybeans for use in optical 3D printing, which usually uses petroleum-derived resins (*Scientific Reports*). The bio-ink can be solidified into a resin by simply treating it with light, and the researchers found it worked well with table-top 3D printers and state-of-the-art ultrafast laser printers at a range of scales.

Printing tissue scaffolds from biomaterials was another active research area in 2020. This involves adding cells and growth factors to liquid biomaterials such as hydrogels that solidify on printing. The cells then start to deposit new proteins around the printed scaffold, eventually producing structures that resemble natural tissues, which can be used to repair or replace damaged ones in the body. Researchers are working on how to improve the biocompatibility, printability, structural stability and tissue-specific functions of these scaffolds.

To this end, a slew of research is investigating making scaffolds from various natural substances. Hyaluronic acid, a natural molecule found in many tissues, has the right properties, but it's not very durable. So US biomedical engineers modified hyaluronic acid and combined it with polyethylene glycol to form a chemically reinforced gel (*Biointerphases*). They envisage a system where hyaluronic acid and polyethylene glycol are the basic 'ink cartridges', which can be used with other 'cartridges' containing specific cells and ligands.

90kg

Just a few drops of cellulose eco-glue can hold up to 90kg in weight



Optical fiber made out of agar

Researchers are also addressing how to fix cells onto the scaffold after printing. Current technology often damages cells or produces structures that don't retain the intended shape for long enough. To address this problem, Japanese researchers added silk nanofibers to various bio-inks and found that the cells retained their 3D configurations after printing, possibly because the silk nanofibers reduced the mechanical stresses placed on cells during the printing process (*Materials Today Bio*).

Inside the body

As medical technology develops, there is increasing demand for biomaterials that can work inside the body. But introducing materials *in vivo* comes with many risks, such as serious infections. Spider silk proteins show great potential here, because they repel bacteria and fungi, as well as helping tissue to heal. This makes them ideal for implants, wound dressings, prostheses and contact lenses. German researchers have demonstrated how to make a material from biotechnologically produced spider silk proteins that pathogenic microbes can't stick to but human cells can (*Materials Today*). This material can work as nano-films and as 3D hydrogel scaffolds for tissue regeneration.

While spider silk proteins are strong and light, elastomers are soft and stretchy, making them potentially useful for repairing tissues and blood vessels. Engineers in the US have designed bio-elastomers that comprise a polymer made from sebacic acid (from castor oil) and 1,3-propanediol (from glycerol), and copper ions, which are involved in blood vessel growth (*Advanced Materials*). Swedish researchers are also working on elastomers, but they're adapting components that have already been shown to work well in the body. Their new rubber-like material could find application in urinary catheters or cartilage replacements (*ACS Nano*).

Various biomaterials are also under investigation for treating bone defects and injuries. Standard bone grafts involve transplanting healthy bone to the damaged area, but the procedure can cause infections, bleeding and nerve damage. An Irish team has developed a novel scaffold that combines collagen with nanoparticles, which can be implanted to aid bone repair (*Acta Biomaterialia*). This scaffold also enhances the immune response, so lowering the risk of inflammation and other complications.

Meanwhile, scientists in the US developed a new type of liposome (derived from natural lipids) for bone repair (*Science Advances*). Liposomes can deliver nutrients and drugs to cells, and this new version delivers oxysterol, a type of cholesterol that plays a key role in skeletal development and bone healing. In tests on mice, this liposome activated bone regeneration without needing therapeutic drugs. ●

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MATERIALS IN 2020

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