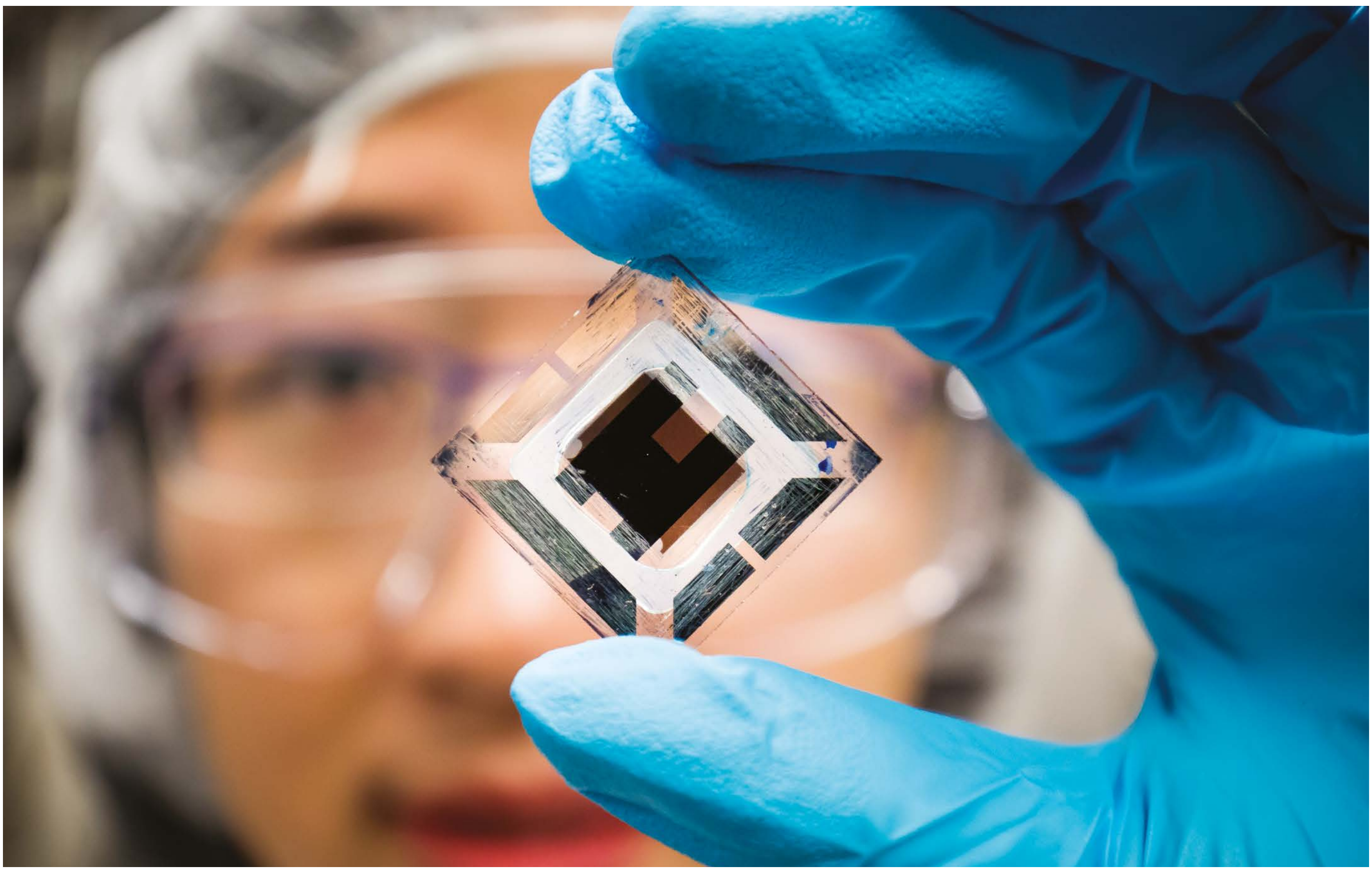
A matter of time and risk

In a material world, scientific discoveries can revolutionize industries, but the road is long. **By Neil Savage**



JOSEPH XU, MICHIGAN ENGINEERING COMMUNICATIONS & MARKETING

Renewable energy conversion rates are improving through breakthroughs in technologies such as organic solar cells.

In the 1960s, the smart advice to a young person in search of a lucrative career was 'plastics', as canonized in the 1967 film, *The Graduate*. Today, the advice might be 'OLEDs' or 'nanomaterials'. In another 20 years, it might be 'graphene' or 'topological materials'.

The hunt for new, commercially viable materials with highly sought-after properties is one of the most competitive pursuits in scientific research. It offers clear applications, strong paths to market and is among the most interdisciplinary of the physical-sciences research fields. Even so, relatively few discoveries, such as organic light-emitting diodes (OLEDs) and, to a lesser extent, graphene, rise above the throng of nascent materials; many languish in the scientific literature.

The stakes are high: a new material in the right place and at the right time can launch a multibillion-dollar industry. Consider what happened for Charles Goodyear. When he mixed sulfur with natural rubber and invented vulcanized rubber in 1839, his discovery gave rise to a multitude of new rubber products with unprecedented tensile strength and elasticity. It advanced the automobile industry, freeing motorists from unwieldy iron wheels. With the smoother ride offered by rubber tyres came the impetus to create the first gas-powered cars. More recently, global industries producing smartphones, wearable medical devices, renewable energy and new aeroplanes have emerged from materials science research.

Artificial intelligence might prove to be the Charles Goodyear of our era. Machine-learning techniques are being used to comb through published research to unearth materials already discovered but forgotten, and to predict the properties of new materials that don't yet exist. This replaces the trial-and-error approaches the field has relied on. According to James Warren, a physicist at the US National Institute of Standards and Technology in Gaithersburg, Maryland, in a very dynamic field it's one of the most exciting developments in recent years.

Warren is director of the Materials Genome Initiative (MGI), a multi-agency project set up by the US government in 2011. The database of materials and their properties is open and available to researchers, to help move those materials from journal pages into potential products, says Warren. "The whole point of MGI is literally to bridge that gap," he says.

In just a few years, he says, it may be possible to tell a computer that you want to build a battery with a certain storage capacity, lifetime and cost, and have it suggest the optimal combination of materials to make it happen.

A long road

It can take decades for a new material to have an impact. The worldwide market for OLEDs reached US$19.45 billion in 2017, and is expected to grow to $81.76 billion by 2026. But, the OLEDS in your TV are a world away from the first experiments in the late 1950s to generate light from organic materials.

Stephen Forrest, a physicist at the University of Michigan, Ann Arbor, who invented phosphorescent OLEDs, is well aware of that. In 1994, New Jersey-based company, Universal Display Corporation, was founded to develop displays based on OLEDs. The company is now valued on the NASDAQ at more than US$9 billion, and has more than 5,000 issued and pending patents worldwide, with offices in the United States, China, South Korea, Japan and the United Kingdom. "The technologies that we had [at launch] were not particularly compelling to the market," Forrest says. "Things happened both within the marketplace and within our lab and it sort of exploded, and now we have a $20-billion global display market based on OLEDs, and every one of them use our materials."

Forrest has helped establish several companies based on his research, covering areas such as organic solar cells, which are lighter and more flexible than their silicon counterparts, and indium gallium arsenide detectors for infrared imaging. But it's not just a matter of creating a new type of material and setting up shop. "You've got to be solving a real problem that people have an interest in," he says. "You can't invent markets through work in the laboratory."

Companies often say it takes at least 10 years for a material to move from the laboratory to the market, says Zhenan Bao, a chemical engineer at Stanford University in California who works with nanomaterials and flexible electronics, including organic semiconductors and carbon-based circuits. In 2010, Bao's lab spun out C3 Nano, a company that makes a flexible, transparent electrode based on silver nanowires. It's being used in some foldable displays and mobile phones available in China, she says, and may soon spread elsewhere. Since she was at Bell Labs (now owned by Nokia) 20 years ago, she has been working on foldable displays that could fit more phone screen in a given space.

Bao's focus has broadened to developing wearable sensors that adhere to the skin and track pulse and other health indicators (see 'Wearing well', page S22), as well as electronic skin, a flexible, transparent material made of a self-healing silicone polymer with a conductive layer. It can sense pressure and send an electrical signal to the brain through an electronic artificial nerve.

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Other materials researchers are developing electronic skin, including Benjamin Tee at the National University of Singapore and Shenqiang Ren at the State University of New York at Buffalo.

Graphene could be an important component of the necessary flexible electronics for Bao's electronic skins. Its unique properties have excited scientists since the material was first isolated in 2004. A one-atom-thick layer of carbon, graphene is stronger than diamond, has the highest electron mobility of any known material, and is more than 97% transparent to wavelengths of light from the ultraviolet to the far infrared. Those properties could come in handy, but so far, no one has come up with an application that has had much of an impact in the marketplace. Grand View Research estimates the global market for graphene was only $43 million in 2017, mainly in applications such as protective coatings for flexible electronics.

The discovery of graphene has, however, opened up research into other 2D materials — atomically thin layers of an element or compound. These may be essential to overcoming the looming end of Moore's law, when the transistors that power computers physically can't get any smaller. Forrest says material that can move electrons more rapidly than silicon will be necessary to keep increasing computing power.

Quantum computing, a fledgling technology based on the laws of quantum mechanics, might benefit from an emerging class called

TOP 5 CORPORATE–ACADEMIC COLLABORATIONS*

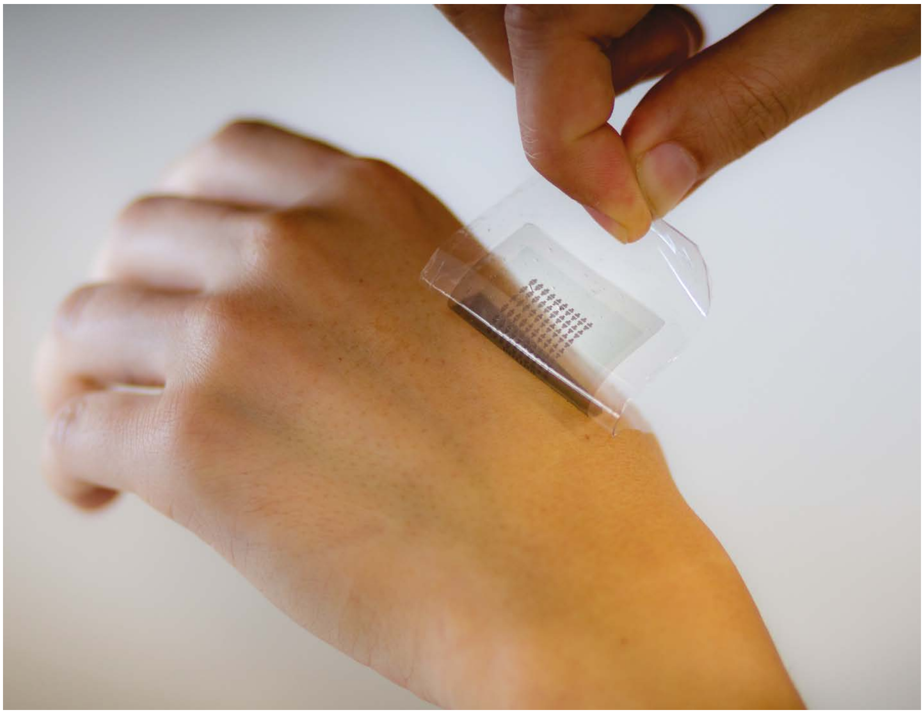
Rank	Institution 1	Institution 2	Countries	Bilateral CS	Count
1	**Samsung Group**	Sungkyunkwan University (SKKU)	South Korea	25.89	32
2	**Center for Nanotechnology GmbH**	University of Münster (WWU)	Germany	20.99	41
3	**Samsung Group**	Stanford University	South Korea/US	13.92	17
4	**Samsung Group**	Korea Advanced Institute of Science and Technology (KAIST)	South Korea	11.91	17
5	**IBM Corporation**	Swiss Federal Institute of Technology Zurich (ETH Zurich)	Switzerland/US	11.12	16

*Date range for data is 2015–18

TOP 5 CORPORATE INSTITUTIONS*

Rank	Institution	Country	Share	Count	Materials Science (%)
1	**IBM Corporation**	United States	112.92	223	59.0%
2	**Samsung Group**	South Korea	49.29	150	76.7%
3	**DowDuPont**	United States	28.34	56	56.1%
4	**Nippon Telegraph and Telephone Corporation**	Japan	20.41	34	34.0%
5	**Toyota Group**	Japan	18.38	47	45.0%

*Date range for data is 2015–18



An adhesive, flexible wearable sensor measures heart and breathing rates.

topological materials, whose electronic structures impart unusual properties. Topological insulators, for instance, conduct electricity on their surface while blocking it from flowing through their bulk.

Google recently demonstrated Sycamore, a computer with 53 quantum bits, which performed a test calculation in just over three minutes that would take a supercomputer running at full capacity much longer (F. Arute *et al. Nature* **574**, 505–510; 2019). To really make a practical quantum computer, though, will take thousands or millions of quantum bits, and topological materials could create the technology to turn that into reality.

Additive manufacturing, also known as 3D printing, is another field that's taken hold in the past few years thanks to materials advances. When it was first developed, 3D printing was used mainly to make prototypes of various tools by having a laser transform powders into a solid, or extruding a thermal plastic through a nozzle. Researchers have since learnt how to work with a variety of materials, including metals and conductive plastics, to make parts for products. Boeing, for instance, is pursuing additive manufacturing as a more cost-effective way to make plane parts, and has invested in 3D printing companies. In 2018, the US aviation giant put money into Digital Alloys, a Massachusetts-based company with a technology that allows it to print different types of metals together to enhance their mechanical or thermal properties.

The multinational manufacturing conglomerate, 3M, which makes everything from transparent bandages to Post-It notes, has great interest in emerging materials innovations, says Greg Anderson, vice-president of its corporate research laboratory in Maplewood, Minnesota. But it usually asks whether an innovation can lead to a new platform, rather than a single product – more a 3D printing technology that can lead to a whole series of products, rather than the one widget made by 3D printing.

Despite the great potential for innovative products, there is significant risk that new materials discoveries will never amount to something marketable. Because of this, many companies like to support their development in small steps, by sponsoring academic research and funding university spinoffs, to see whether the technologies that emerge are worth more significant investment, Anderson explains. "We'll do sponsored research to help us mitigate the risk," he says. "We'll spend a little bit of money in partnership with the university to advance the science and see how feasible that technology is."

"In academia, we can dream something really big. What we do could be science fiction," says Bao. "But some of those [ideas] could be turned into reality. That depends on the company and their creative thinking of how to use some of the crazy things that we invent."

Neil Savage is a freelance science writer in Lowell, Massachusetts.

Wearing well

Stretch goals of a long-time partnership yield flexible electronics breakthroughs.

Stanford University's Zhenan Bao is taking wearable electronics to a radical new level inspired by skin — flexible, stretchable and unobtrusive. In August 2019, she and her team detailed a wearable sensor in the form of a sticker. It measures heart and breathing rates, and transmits this information via a flexible antenna and a radiofrequency identification tag to a receiver clipped to the wearer's clothes.

The device, described in *Nature Electronics* (S. Niu *et al. Nature Electron*. **2**, 361–368; 2019), is the latest milestone in Bao's long-running collaboration with the South Korean conglomerate, Samsung, and its in-house lab, the Samsung Advanced Institute of Technology in Suwon.

Bao's team had been working with Samsung on carbon nanotubes — cylindrical sheets of carbon atoms — for a decade when she pitched an idea for stretchable electronics in 2014. These were to be more than just rigid components with flexible joints, they were conceptualized as skin-like, intrinsically stretchable materials. This was a continuation of the previous work, as carbon nanotubes could be incorporated into such materials.

Samsung signed on. Its work with Bao and others has become a mainstay of the most productive international corporate–academic collaboration in the Nature Index. Bao describes the financial support as "substantial". For decades Samsung has funded research at South Korean universities, and it acquired one of the nation's leading institutions outright, Sungkyunkwan University, which has campuses in Seoul and Suwon. Samsung sponsors research worldwide through its Global Research Outreach programme, open to all researchers.

In the early stages of the collaboration on stretchables, Samsung set performance targets for the electrical conductivity of the material that would be required to design viable products. Bao admits that she initially thought they were impossible, "but this kind of impossible target can make us more creative", she says.

Mark Zastrow