A flexi-screen mobile phone is on display at an exhibition in Chengdu last year.

WANG XIAO/CHENGDU ECONOMIC DAILY/VCG/GETTY

The materials reality of China

Scientists are discovering how to fulfil their ambitions in a system that is rapidly modernizing.

BY SARAH O'MEARA

By the time Dawei Zhang's study visa to the United States had been renewed, it was too late. The 29-year-old materials scientist was back in China with his wife and son, ready to begin a postdoc at the University of Science and Technology Beijing — one of the country's leading materials institutes. The delay had prompted him to accept a position in China, rather than pursue research on self-healing materials in the United States.

Looking back, Zhang realizes that the unexpected move worked out well for him. Six years later, his research into materials corrosion has become part of a national 1-billion-yuan (US$150-million) programme to revolutionize the speed and efficiency with which China can develop new materials, known as the Materials Genome Engineering (MGE) project.

Such large-scale scientific ventures have become common in China over the past decade, forming key elements of the government's plan to transform the country into a high-tech economy that can match, and eventually surpass, the world's leading scientific nations.

Launched in 2016, the MGE aimed to match the scope of the Materials Genome Initiative in the United States, a $250-million federal programme designed to shepherd advanced materials science into industrial applications. The names are intended to draw comparisons to biological superprogrammes such as the Human Genome Project. In essence, China's policymakers want to make better use of the information stored in the country's databases about the behaviours of materials, so that new materials can be developed.

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More on China's materials scene
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But the researchers are still at an early stage. Zhang's team struggles to understand the methods of data scientists — a problem, he says, that is common across the world.

"When we were preparing the proposals for MGE, we were aware of this, but it wasn't until we started working on it that I realized this would be a long-term issue."

The students in the laboratory often do better than the more experienced ▶

professors, says Zhang. “They have time to go off and study these new ideas in depth.”

A final goal of the MGE, he says, is to develop a centralized, intelligent data-mining software platform that can offer instant feedback to companies involved in, say, car manufacturing, steel-making and shipbuilding, on how materials behave.

At his lab at the Institute of Advanced Materials and Technology in Beijing, Zhang works in a cross-disciplinary team, some of whose members focus on the MGE (see ‘Hard data’) while others do basic research. Data scientists help him to process the information in the databases to aid the creation of models for new materials, and biologists look at the influence of microorganisms on corrosion. His institute also welcomes guest professors from the United States and Europe.

It’s the kind of diverse, multidisciplinary community, Chinese scientists say, that is crucial to doing great research but is often lacking in labs. “The goals of the Materials Genome Initiative in the States and in China are the same: to produce better materials more quickly that cost less. It’s very important we collaborate with overseas scientists because the materials genome is a new topic. We need to figure out the best path together,” says Zhang.

A CLEAR FUNDING PLAN

Funding for materials science in China has quadrupled since 2008, and the field receives the second highest level of funding from the National Natural Science Foundation of China (NSFC), behind only medical sciences (see ‘China’s funding boost for materials’). The volume of China’s materials-science research has grown correspondingly. According to data from the Web of Science, the number of papers on the topic more than tripled between 2006 and 2017, to around 40,000 (see ‘Big progress’), and around one in every nine papers published by a Chinese researcher in 2015 was in materials science.

HARD DATA

A history of materials

1980s: Chinese universities and research institutes develop 23 small-scale materials databases with financial support from the national government. They are used and updated infrequently.

2000: China launches two national, centralized materials databases involving 18 research institutes. For the first time, data are collected and entered in a standardized format (see http://www.materdata.cn).

2016: Policymakers invest in developing databases and big-data technology for China’s Materials Genome Engineering project, which echoes the Materials Genome Initiative launched by then-US president Barack Obama in 2011.

Since 2006, China’s scientific research and development (R&D) funding has been guided by a national plan to improve the country’s level of innovation by 2020. The plan includes the realization of ambitious research and development projects, such as Moon exploration and the development of China’s first domestically designed passenger aircraft. These goals are designed to spur technological breakthroughs and improve the country’s economic prospects, and materials science is crucial to their success.

In 2018, the NSFC pumped more than 2 billion yuan into 701 projects, including the MGE and work on nanotechnology and advanced electronic materials. In the same year, the Ministry of Science and Technology announced total funding of more than 1.6 billion yuan for six special projects, which also covered nanotechnology.

China now publishes more high-impact research papers than any other country in 23 fields with clear technological applications, including batteries, semiconductors, new materials and biotechnology (see go.nature.com/2xuboa9). And in November, a start-up called Qing Tao Energy Development, begun in 2014 by PhD graduates from Tsinghua University, Beijing, announced that it had developed the country’s first solid-state battery production line.

Yet, despite the country’s growing impact, it’s not clear whether China’s scientists are achieving as much as they could, given their resources. John Plummer, a former senior editor for *Nature Materials* based in Shanghai, who is now a senior portfolio editor at Nature Research, acknowledges that China is a leader in some areas of materials science — such as nanomaterials, condensed-matter physics and structural materials. But it does not yet compare to the United States or Europe in terms of materials research overall, he says.

Jia Zhu, a nanomaterials scientist at Nanjing University, says: “We need to do more to promote original ideas. In the US, when they start a new programme or research, they won’t look at other people and say, ‘They’re doing that, so we should do that.’ In China, we still do that.”

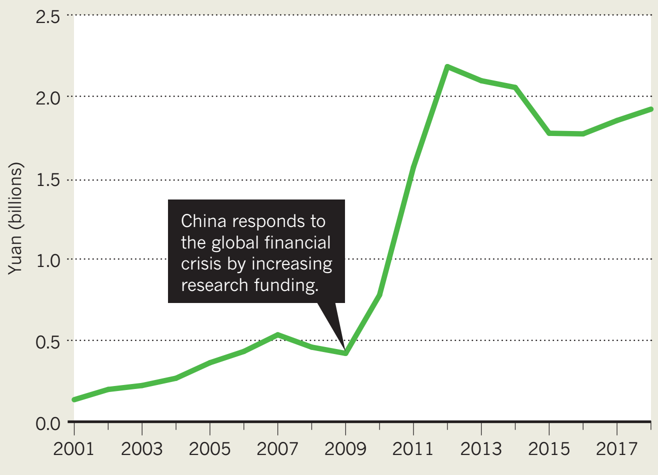
TIME TO TAKE A RISK?

In 2014, geophysicist Ho-Kwang Mao began splitting his time between the Carnegie Institution in Washington DC and Shanghai. After more than 50 years working in the United States, he was hoping to help Chinese officials solve one of the country’s most pressing R&D problems. “They asked me: ‘What can we do to improve fundamental research in terms of quality, not just quantity?’ ”

The scientist, who was born in Shanghai, studies how materials respond to extreme

CHINA’S FUNDING BOOST FOR MATERIALS

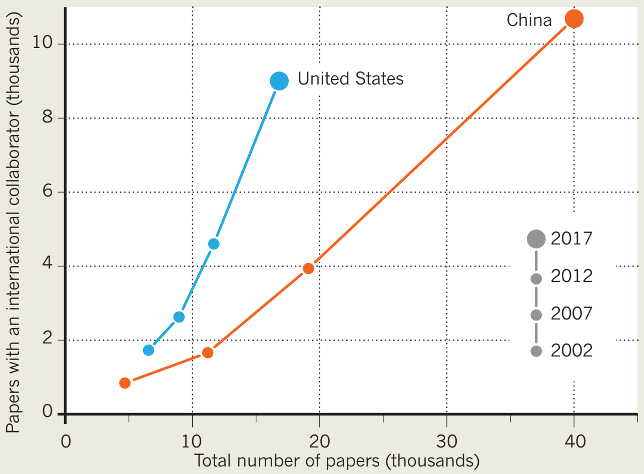
Engineering and materials science have received, on average, the second highest level of funding from China’s National Natural Science Foundation since 2001.



SOURCE: NATIONAL NATURAL SCIENCE FOUNDATION OF CHINA

BIG PROGRESS

China’s output of materials-science papers far outstrips that of the United States, but international collaborations are relatively sparce.



SOURCE: WEB OF SCIENCE

pressure, and told officials that they should give him the money to start a lab to produce “truly transformative research”. He explained that there would probably be no immediate breakthroughs. His only guarantee was that he would attract scientists from all over the world who had the same potential for productivity that he himself has demonstrated: during his career, Mao has had 65 papers published in *Nature* and *Science*.

“Give me the money and I’ll give you the scientists,” he said in 2008, at an event held by the NSFC and the Chinese Academy of Sciences (CAS), the largest scientific organization in the country and a policy adviser to the government; Mao was made a member in 1996. The officials gave him the money — and in 2013, the Center for High Pressure Science and Technology Advanced Research (HPSTAR) was established, with branches in Shanghai and Beijing. Mao’s labs are not funded through the usual central bodies, such as the Ministry of Science and Technology, but directly by the Ministry of Finance.

Mao says that he has attracted staff scientists from countries including Canada, Egypt, Germany, Japan, Russia, the United Kingdom and the United States. “In China, the system was not very effective for support of fundamental research. I was allowed to try a new system that gives scientists total freedom to pursue transformative science in their own way with minimal supervision, reviews and evaluations. Of course, the government is keeping an eye on how we progress, but it’s low-key.”

Mao’s radical approach to funding removed one of the major structural barriers that inhibit innovative materials research. In China, scientists’ funding prospects depend largely on how many papers they have published in high-impact journals, says Zhenhai Wen, a CAS chemist who researches methods of energy storage at the Fujian Institute of Research on the Structure of Matter in Fuzhou. “Junior researchers must survive the intense competition for funding, so we have to pursue hot topics of research, even though that means our work might not be innovative and [might] overlap with others’.”

Mao is convinced that scientists perform better without restrictions — and the opportunity to do just that was partly why physicist Philip Dalladay-Simpson applied for a position as a postdoc with the Shanghai lab, to study the response of molecular systems to very high pressures. He graduated from Queen Mary University of London in 2010, and finished his PhD — on how hydrogen responds to extreme environments — at the University of Edinburgh, UK, in 2016, just as HPSTAR was undertaking a recruitment drive.

“This was a chance to align myself with a new and ambitious research institute, where I could have the freedom to research my ▶

STEFEN CHOW FOR *NATURE*

Q&A

Printing pioneer

Chemist Yanlin Song uses nanomaterials to reduce the pollution caused by conventional printing processes. Nature *speaks to him about his work at the Chinese Academy of Sciences Institute of Chemistry in Beijing and why it matters to China.*

How does your technology work?
The printing industry uses a high volume of chemicals and produces a lot of waste. These can be hazardous for the environment. We have created a coating, using nanomaterials, to eliminate the need to chemically treat the printing plates that are used to transfer a design to paper.

What results have you had?
We’ve developed a range of green printing applications, from plate-making and electronic printing technology to green printing processes for packaging and 3D printing. Our work has been included in China’s road map for developing the printing industry, and some universities, such as the Beijing Institute for Graphic Communication, have developed a curriculum around our research.

Who funds your lab?
My funding mainly comes from the Ministry of Science and Technology, the Chinese Academy of Sciences, the National Natural Science Foundation of China and the Beijing Municipal Government. I also receive financial support from companies such as Procter & Gamble and Samsung. Last year, my lab received US$3 million in total.

What research obstacles are you facing?
There are still many fundamental problems that need to be solved for green printing technology. Most of the challenges have to do with the way in which liquids behave at very small scales. For example, the nozzles used in conventional inkjet printing can produce droplets only 10 micrometres in diameter or larger. This makes it difficult to print at smaller scales, which in turn limits our ability to produce complex electronic circuits for chips and smart textiles such as wearable sensors.

How is your research being applied?
I’m working with four companies on different applications. There are two main obstacles: fabricating products on a large scale while maintaining quality, and persuading people to buy them. Customers tend to want the most cost-effective product rather than the most high-tech version. This is a challenge for researchers. So far, our green printing-plate technology has been used by China’s national news agency and our electronic printing processes have been used to produce transport tickets in Beijing and Hong Kong.

What are you currently working on?
We’re developing 3D inks that can be printed directly on paper to create braille text. Conventional mechanical processes for printing books in braille are specialized and expensive and the books don’t last long as the embossed dots become flattened by touch. These factors have led to an extremely limited number of braille books in our country. My friend has children who are blind and I’ve been thinking about the problem for a long time. We hope our process will greatly lower the printing costs and improve the printing quality. ■

INTERVIEW BY SARAH O’MEARA

This interview has been edited for length and clarity.

personal interests. It felt daunting as it wasn't something I had ever envisioned for my career," Dalladay-Simpson says.

Mao's team can take advantage of one of China's growing list of large-scale research projects — the 1.2-billion-yuan Shanghai Synchrotron Radiation Facility, which opened in 2009. Here, HPSTAR scientists use X-rays to learn more about how materials react under pressure. "Our team use the facility monthly, at least, so we rented lab space next door," says Mao.

THE PRESSURE TO PERFORM

For engineer Guang Chen, China's ambition to become a global leader in science and technology by 2049, the centenary of the founding of the People's Republic, is a daily pressure.

The country wants to manufacture its own aircraft from scratch: at present, commercial planes made by Chinese companies use imported engines. So, when Chen, who works at Nanjing University of Science and Technology, published a paper in 2016 about a new alloy that could be used in the manufacture of jet engines (G. Chen *et al. Nature Mater.* **15**, 876–881; 2016), his funding rocketed.

In 2017, Chen was promised key funding worth 3 million yuan, five times the value of the general grants usually awarded by the NSFC. In addition, he received two of these 600,000-yuan grants. Although he is pleased to have the support he needs, he knows there will be consequences if he sees no results by the time his funding runs out. "It will hurt my scientific reputation and applications for later programmes," he says.

Chen has been working in this area for more than 20 years, and speculates that commercialization could take another 10. But that's not the kind of speed that the Chinese government or industries have come to expect from their country's developers, says Xingyu Jiang, a chemist at the Southern University of Science and Technology in Shenzhen.

"If you have a high output in fundamental research, there's an expectation that you'll have an equally high level of products. That's how many officials and private funders think. But a lot of products that we use today are based on research done 20 or 30 years ago," he says. "In China, we have fewer large companies who will make the necessary investment in R&D to push products to market."

> "WHAT CAN WE DO TO **IMPROVE** FUNDAMENTAL RESEARCH IN TERMS OF **QUALITY,** NOT JUST **QUANTITY?"**

For scientists in China, moving bench research towards a high-tech production line is not straightforward. Neither government nor business is hugely experienced in commercializing technology, and researchers struggle to meet high expectations without the infrastructure and expertise to support them.

Wen came back to China in 2014 after doing postdoctoral research at the University of Wisconsin–Milwaukee in electrochemical-energy conversion and storage. Since returning, he's been encouraged to cooperate with businesses and invited to meetings with local government officials, to discuss the commercial applications of his research into the development of batteries and fuel cells.

They have offered to support a start-up venture, or smooth the way for collaboration with a local company. But Wen is wary of pitfalls. "Starting a company is easily accomplished. I've seen many companies fail due to inexperience in large-scale production, poor management and a lack of a market for the products."

The government has introduced incentives to encourage scientists to start businesses, such as financial stakes in spin-off companies and time away from their lab to develop the technology, but the environment is still tough.

Wen thinks that more should be done to increase understanding between research teams and manufacturing companies: "The development of new materials in the lab often takes insufficient account of market demand, making it difficult to get financial support from companies," he says.

NANOMATERIALS GET BIG

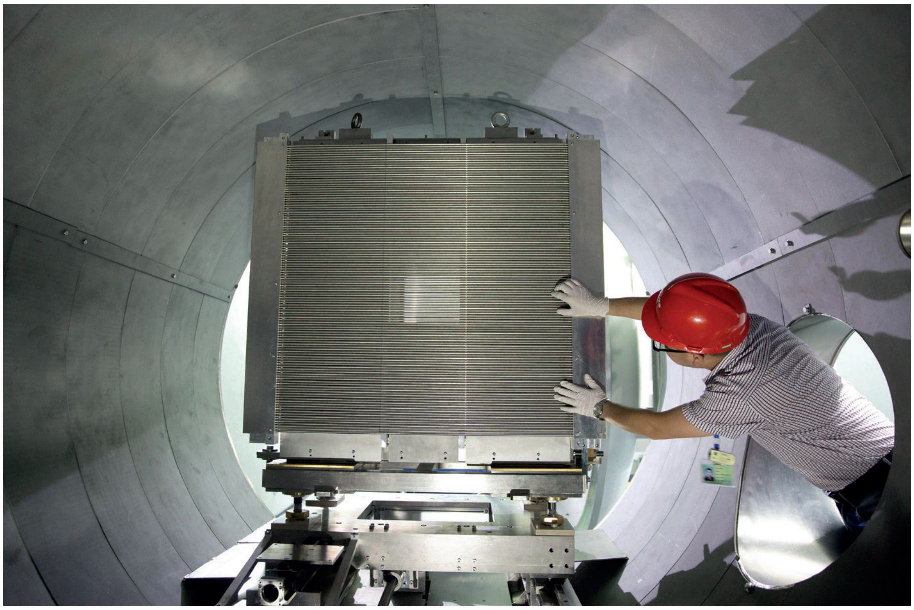
When the scientists who developed graphene at the University of Manchester, UK, won the Nobel Prize in Physics in 2010, their creation was widely expected to revolutionize electronics. The ultra-light, flexible, strong and highly conductive nanomaterial has not yet lived up to expectations — but, if it does, China intends to be perfectly placed to take advantage.

China recognized the contribution that nanoscience discoveries could make to its own scientific, technological and economic development early on. In 2003, the CAS and the Ministry of Education established the National Center for Nanoscience and Technology, and the country now has the highest number of graphene businesses in the world — nearly 3,000, according to government figures. The country also accounts for around two-thirds of global production.

But there's a problem: almost all these producers are small or medium-sized companies that will lack funding in the long term unless they find a sustainable business model, says chemist Xiaoyue Xiao.

In 2013, Xiao and Yichun Li, a materials engineer now at the China International Technology Transfer Center in Beijing, came up with the idea of forming an organization to enable these companies to work together and grow. "The good thing was there were lots of small companies working on graphene or graphene-related technologies. The bad thing was that quite a few of them couldn't keep going," Xiao says.

In the same year, Xiao and Li founded the China Innovation Alliance of the Graphene Industry (CGIA) to bring together universities, institutes and companies in an attempt to improve the situation. "Investors were putting in lots of money, but then quickly became frustrated because companies were struggling to develop applications they could



An engineer debugs an instrument at the China Spallation Neutron Source in Dongguan; scientists use accelerators such as this and the Shanghai Synchrotron Radiation Facility to study materials' behaviour.

XINHUA/ALAMY

sell," says Xiao.

Ou Mao works at Cnano Technology, a company with corporate headquarters in Santa Clara, California, that mass-produces carbon nanotubes and graphene using techniques developed by chemical engineers at Tsinghua University in 2001. The company now has an annual revenue of more than $50 million. Mao has more than 20 years' experience in industrial R&D, and says that the team has focused on ensuring that its products suit the market: "We know that carbon nanotubes have many potential applications across all industries, but it may take many years for industries to accept these novel materials, both in terms of technology and regulations. So we have to be smart and selective in choosing our target market and applications."

The CGIA put together a database of graphene-related projects, categorized by their development stage: lab, pilot or commercialization. Projects at each stage receive a different type of support. Lab projects are tracked and given an incubator when ready; at the pilot stage, the CGIA helps to find investment; and at the commercialization stage, it invites project teams to present their work in front of potential investors and government representatives. The alliance has an annual operating budget of 8 million yuan.

Xiao points to advances in areas such as flexible display screens as examples of successful product development: "We have three members — Chongqing Graphene Technology, Wuxi Electronics and Instruments, and 2D Carbon Tech — all with the ability to industrially produce graphene flexible screens, and are negotiating cooperations with well-known Chinese electrical appliance manufacturers."

The next stage for the CGIA is to tackle one of the industry's biggest problems — which, as Xiao puts it, is that "the quality of graphene products is totally uncontrollable". In 2016, he therefore helped to launch the China International Graphene Industry Union, which is developing the country's first set of standards. He is also discussing how to reduce technical barriers to trade and joint R&D with international teams such as the International Electrotechnical Commission in São Paulo, Brazil.

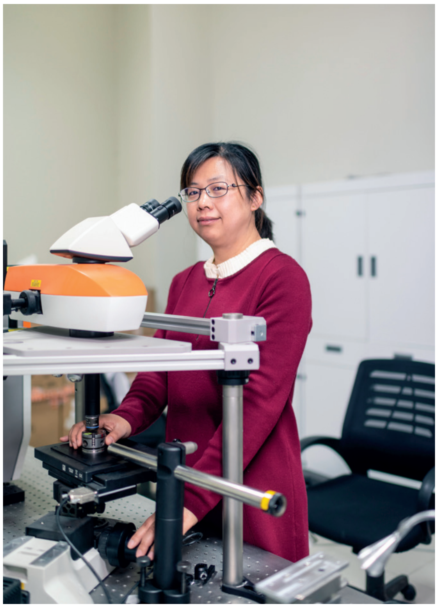
"Right now we are working on setting up an international standardization evaluation committee. I think this will help us to speed up the technology transfer from lab to industry," Xiao says. What China's materials science needs now, he adds, is exposure to the rest of the world's scientists. "We need to work on this together as a global group. You cannot just close your door to working on something. People need to know what you're doing." ■

Sarah O'Meara *is a freelance science writer in London. Additional research by Kevin Schoenmakers.*

Q&A

Pressure chemist

Chemist Haiyan Zheng works for the Center for High Pressure Science and Technology Advanced Research (ÎHPSTAR) in Beijing. Nature *talks to her about her work at the institute and about equality in science in China.*



STEFEN CHOW FOR *NATURE*

How did you come to work at HPSTAR?
After completing my PhD in organic chemistry at the Chinese Academy of Sciences Institute of Chemistry in Beijing, I moved to Rice University in Houston, Texas, to study carbon nanomaterials for the purposes of drug delivery. At the same time, my husband was doing his postdoc at the Carnegie Institution for Science in Washington DC under Ho-Kwang Mao, who founded HPSTAR. He introduced me to his research. The following year, I joined Mao's group as a postdoc and began learning about high-pressure technology, and in 2014 came to work at HPSTAR as a staff scientist.

Why did you change your research field?
High-pressure chemistry is an unexplored area of research, which I really feel needs to be investigated. It's an amazing opportunity for a researcher. Changing my field also meant a chance to work near my husband, which was good for our home life.

What are you working on?
Everyone at HPSTAR works on different areas of high-pressure science and technology. My job is to better understand how basic organic chemicals react under extreme conditions, including high pressure and high temperatures. In theory, this research could lead to the creation of compounds or carbon structures with new properties.

How much has your scientific focus changed?
I still focus on chemistry, just using a different tool. I would now describe my work as physical chemistry. At HPSTAR, we have chemists, physicists and materials scientists all working together to better understand the relationship between the structure of materials and their properties.

What is the goal of your work?
My team and I would like to understand precisely how chemical reactions happen under extreme conditions, then design molecules that will be compressed under high pressure and produce the desired product. That's our dream.

What are the obstacles for Chinese women in science?
Your early thirties are a very important time for the development of your career, but it's also the time when women have children. This can cause difficulty, because women can't focus all their energy on work. I'm very lucky. My husband works in the same institute, so that helps us to balance our family and work lives more efficiently. We can discuss our work at any time. Our parents also help us a lot with the care of our four-year-old son.

What does a female scientist need to succeed?
To be a successful women in science, you need three things: self-motivation, equal opportunities at work and family support. You also need to have a work environment that supports you, and people to help you with family life.

Do women in science receive additional support in China?
The government tries its best to support women in science. In 2011, the National Natural Science Foundation of China committee increased the age limit for women applying to its Young Scientist Fund from 35 to 40. In the past, everyone had to apply before they reached 36. That's hard for women because of their responsibility for children around that time. After the age limit increased, the number of successful applications from women increased by ten percentage points. I think that it has been a great help for women in their careers. ■

INTERVIEW BY SARAH O'MEARA

This interview has been edited for length and clarity.

CORRECTION

The Spotlight article ‘The materials reality of China’ (*Nature* **567**, S1–S4; 2019) made several mistakes. Ho-Kwang Mao was born in Shanghai, not Taiwan. Guang Chen is at Nanjing University of Science and Technology, not Nanjing University. And Zhenhai Wen did his postdoctoral research at the Milwaukee campus of the University of Wisconsin, not the Madison one.