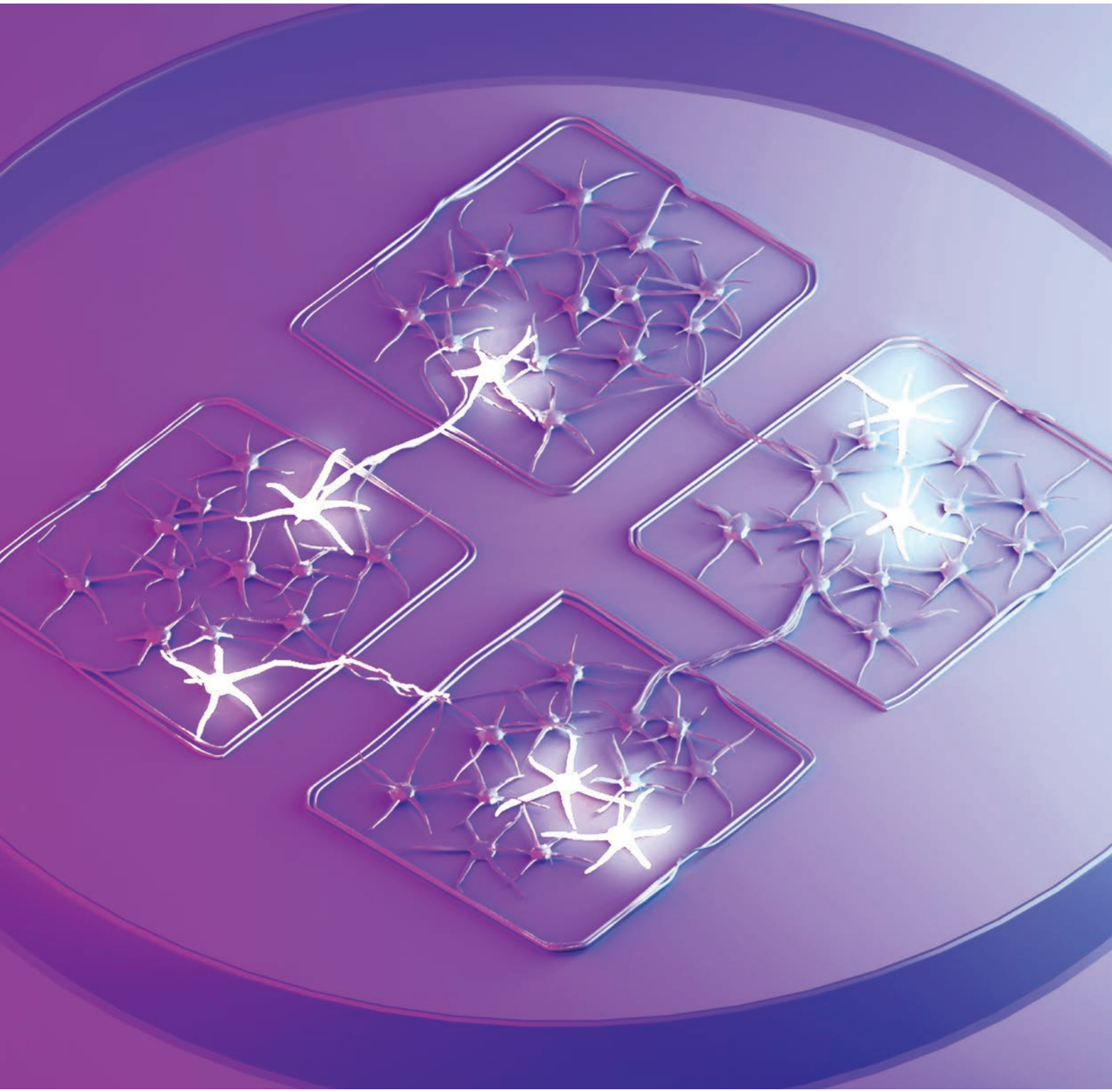
AiM Research

RESEARCH HIGHLIGHTS 2019

A publication of the WPI Advanced Institute for Materials Research



AIMR

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TABLE OF CONTENTS

MESSAGE FROM THE DIRECTOR

1 Pursuing excellence in materials science on a global stage

SPECIAL SECTION

2 Director's interview: Building on an impressive legacy

RESEARCH HIGHLIGHTS

5 Neuroscience: Neuronal networks in dishes

6 Crystal structure: Fourth crystallographic phase uncovered

7 Spintronics: Magnetic tunnel junctions go ferrimagnetic

8 Lithium batteries: Electrode boosts storage capacity

9 Lithium batteries: Complex hydride promising as solid electrolyte

10 Topological phases: Two new fermions discovered

11 Nanoporous graphene: High strength and flexibility achieved

12 Topological insulators: Imaging nanoscale domains on a multilayer structure

13 Electrochemical water splitting: Mathematically designed graphene on edge

14 Magnetic materials: A magnet that can twist and turn

15 Metallic glasses: Discovering better combinations faster

16 Fuel-cell catalysts: Surpassing platinum

17 Iron-based superconductors: Ruling out a cause for high-temperature superconductivity

IN THE SPOTLIGHT

19 Seeking synergies between fields and countries

22 Promoting interaction between material scientists in Europe and Japan

WPI Advanced Institute for Materials Research

The Advanced Institute for Materials Research (AIMR) at Tohoku University in Sendai, Japan, was launched in 2007 as one of the centers established by the World Premier International Research Center Initiative (WPI) with the support of the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT). Since then, the AIMR has been bringing together world-class researchers from Japan and abroad to carry out cutting-edge research in materials science through interdisciplinary collaboration among its four materials-related groups — Materials Physics, Non-equilibrium Materials, Soft Materials, Device/System — and the Mathematical Science Group.

In 2017, the AIMR became a member of the WPI Academy, which consists of WPI centers that have achieved world-premier status. The institute will continue to maintain its world-class research environment and further promote global brain circulation.

Led by distinguished material scientist and director Shin-ichi Orimo, the institute promotes interdisciplinary research across the different groups. It also fosters young researchers through the Global Intellectual Incubation and Integration Laboratory (GI^3 Lab). This unique program, which is currently supported by the WPI Academy, promotes international joint research conducted in close cooperation with high-profile researchers invited from countries around the world.

The AIMR is host to about 100 leading researchers, around 40 percent of whom come from abroad, including 25 principal and junior principal investigators. In addition to the research hub at Tohoku University, the AIMR collaborates with research centers in China, Germany, Poland, the UK and the US. Close ties with other leading overseas institutes are maintained, going along with the efforts of foreign principal and junior principal investigators, as well as adjunct professors and associate professors.

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MESSAGE FROM THE DIRECTOR

Pursuing excellence in materials science on a global stage

The Advanced Institute for Materials Research (AIMR) was founded in 2007 with support from the World Premier International Research Center Initiative (WPI), a Japanese government program for establishing world-class research centers. Since then, AIMR has been advancing WPI's four objectives: advancing top-level research, creating interdisciplinary domains, establishing international research environments, and reforming research organizations. It has become a center for materials science that attracts outstanding researchers from all over the world. In 2017, AIMR became a member of the newly established WPI Academy, and has maintained world-class standards as it drives efforts to accelerate and expand the international circulation of the world's best brains.

As an international center for materials science, AIMR stands out through its ambition to promote collaboration between mathematics and materials science. By employing the universal language of mathematics to describe the extremely broad field of materials science, we aim to identify the commonalities among a variety of materials and pursue new topics to produce novel research outcomes. Institute-level initiatives that seek to establish collaborations between mathematicians and materials scientists are rare; and our efforts are emblematic of AIMR's status as a progressive center for materials science.

Having been officially recognized by the Japanese government as a Designated National University in June 2017, Tohoku University is expected to pursue educational and research activities at the highest international level as one of Japan's leading universities. The university is making steady progress in bolstering its research capabilities by establishing core research clusters in four fields: materials science, spintronics, next-generation medicine and disaster science. AIMR is playing a leading role in establishing the materials science research cluster, collaborating with other institutes and departments to launch five new projects on energy materials, electronic materials, biomaterials, materials development based on texture control, and high-strength materials.

To advance these activities, AIMR partnered with the spintronics research cluster to hold the 2nd Symposium on Materials Science and Spintronics in February 2019. It was attended by more than 250 researchers from seven countries. Particularly notable among the 18 guest speakers were Professor Alan Lindsay Greer of the University of Cambridge in the UK, principal investigator at AIMR and a world authority on microstructure formation of metallic materials, and Professor Kang L. Wang of the University of California, Los Angeles, who is celebrated worldwide for his discovery of chiral Majorana fermions and spintronics research. Stimulating discussions took place about the very latest research on materials science and spintronics — AIMR's key focus since its founding.

In May 2019, AIMR partnered with three other materials-related WPI centers to run a joint booth at the European Materials Research Society (E-MRS) Spring Meeting in Nice, France. This enabled AIMR to interact with many researchers from all over Europe. In the following month of June, the French CNRS National Competency Cluster in Nanoscience (C'Nano) joined the four WPI centers, which included AIMR, to hold the 13th Japan–France Workshop on Nanomaterials and the 4th WPI Workshop on Materials Science (NanoMat 2019) in Paris, France. At this workshop, French and Japanese researchers gave presentations, furthering their research-based exchange. Through multinational events such as these, AIMR is strengthening its global network and fostering an international outlook, both of which are among its key objectives.

I would like to thank all those who have lent us their support. At AIMR, we are playing a central role in Tohoku University's efforts to establish an international research environment as a Designated National University. We intend to redouble our efforts to pursue high-quality research as a hub facilitating international circulation of the world's best brains, and contribute to cutting-edge materials science and societal advancement.

Shin-ichi Orimo, Director
Advanced Institute for Materials Research, Tohoku University

DIRECTOR'S INTERVIEW

Published online on 23 December 2019

Building on an impressive legacy

Shin-ichi Orimo, who assumed the helm of the AIMR earlier this year, shares his vision for the institute's future

In October 2019, Professor Shin-ichi Orimo became the third director of the Advanced Institute for Materials Research (AIMR) at Tohoku University in its 12-year history. He succeeded Professor Motoko Kotani, who had been director of the AIMR since 2012. They are big shoes to fill. "Under her guidance, researchers at the AIMR produced many outstanding results," Orimo notes. "The excellent quality of this research brought us worldwide recognition."

But Orimo is ideally positioned to assume the directorship of the AIMR. For a start, he has enjoyed a long relationship with the AIMR. His laboratory at the Institute of Materials Research, which is also at Tohoku University and just a short stroll from the AIMR, is seeking to research and develop hydrogen functional materials for energy devices such as fuel cells and all-solid-state secondary batteries. Over the years, his team has collaborated extensively with AIMR researchers. "As the leader of the Device/System Group at the AIMR, I have participated in many joint research projects and have strengthened collaboration with others on our teams," Orimo says.

Continuing an interdisciplinary legacy

Orimo is keen to continue the interdisciplinary emphasis that the AIMR has been focusing on, namely the two-way interaction between mathematics and materials science. "This approach has more than proved its worth," he says. "My aim is to further advance the collaboration between mathematics and materials science and to link this to the creation of new materials."

Orimo's vision is to use materials science to provide various solutions to the problems faced by society today.

Orimo is very conscious of the valuable insights that mathematics can bring to materials science through his own research topic. "Molecular dynamics calculations are extensively used to investigate ion mobility in materials," he explains. "At the AIMR, we are using a mathematical perspective to identify structural characteristics with a focus on mobility randomness to obtain a more fundamental understanding." This is just one example of the symbiotic relationship between the two fields: "We are really interested in two-way research, namely the application of mathematics to materials, and materials to mathematics."

One practical link being forged between mathematics and materials science is the recent appointment of a renowned mathematician, Professor Hiroshi Suito, as deputy director of the AIMR. He is a leader at the Mathematical Science Group of the AIMR.

Another conduit is the establishment of three Advanced Target Projects (ATPs) that will address the control of local structure in topological functional materials; the integrated control of bond variation and its time evolution; and improving self-organization technology and controlling biological responses. "These projects not only build on the knowledge and methods gained in AIMR's conventional research, but they also go further by employing mathematical techniques that are easier to apply to material creation," Orimo says. He notes that the three ATPs respectively address phenomena on the micro, meso and macro scales. "Our ultimate goal is to create materials based on a complete understanding and control of atoms and molecules — the smallest units for materials," Orimo says. "To reach this goal, the ATPs aim to create materials that express new functions by connecting our understanding and ability to precisely control atoms and molecules to phenomena on the meso and macro scales."

Enhancing international collaboration

Another major emphasis of the AIMR has been the adoption of a global outlook through strengthening ties with overseas researchers and institutes. The institute has established three joint laboratories with overseas institutions: one with the University of Cambridge in the UK with a focus on non-equilibrium materials and computational materials science, another with the University of Chicago in the US that specializes in spintronics, and a third with Tsinghua University in China focusing on topological materials.

Shin-ichi Orimo is eager to develop even stronger ties between the AIMR and industry.

Orimo intends to continue to pursue international collaboration. "I hope to develop exchange relationships with overseas universities and research institutions, especially those in Switzerland and France," he says.

Strengthening partnership between academia and industry

The AIMR has an excellent track record of applying research outcomes to industrially relevant problems. Orimo is no stranger to collaboration with industry. His research team has collaborated with a wide range of companies, including those in the materials, electricity and vehicle industries. And he is working on creating a research platform between industry and academia. "I want to deepen cooperation with industry by further strengthening ties with university–industry collaborative organizations at Tohoku University," he comments. "Collaborating with industry is critical for creating materials that contribute to society."

"MY VISION IS TO LEAD THE AIMR TO THE NEXT STAGE AS THE WORLD'S LEADING INSTITUTE FOR MATERIALS SCIENCE."

Focusing on 'three Rs'

Speaking of his vision for his directorship, Orimo refers to 'three Rs': **R**elief, **R**esearch and **R**ecognition. The first 'R', Relief, refers to the holistic welfare of everyone at the institute, including their physical safety and mental well-being. The second 'R' is for research, which must stay as close to the frontiers of current knowledge as possible. "Being at the edge of the research front means being at a cliff edge at the same time," Orimo explains. "It is crucial that we always stay alert to that fact." Finally, the third 'R' is recognition, which involves actively publicizing research results, so that the AIMR gains an even higher profile both in Japan and abroad.

"My vision is to lead the AIMR to the next stage as the world's leading institute for materials science by strengthening collaboration between materials science and mathematics, while advancing the discovery and development of new materials through the utilization of advanced measurement technologies," explains Orimo. "In light of the problems we face today, I hope to provide various solutions in collaboration with our members," he adds." ■

RESEARCH HIGHLIGHTS

The AIMR advances research in materials physics, non-equilibrium materials, soft materials and devices/systems, and actively promotes collaboration among these divisions toward the development of groundbreaking technologies that cross the boundaries of conventional fields of study — bridging the disciplines of materials science, physics, chemistry and precision, mechanical, electronics and information engineering. The Mathematical Science Group further complements the AIMR's research activities.

Neuroscience:

Neuronal networks in dishes

A simple model of the brain consisting of four circuits of rat neurons reveals how the brain strikes the right balance between two processing strategies

By precisely engineering the interface between living cells and a glass coverslip, AIMR researchers have constructed small circuits of rat neurons in a dish[1]. This allowed them to mimic the way neurons are connected in the brain, revealing important insights into the mysterious field of brain dynamics.

The human brain is made up of specialized regions that process signals from different sources. For example, one region of the brain processes the colors our eyes see, while another region processes language.

But in addition to this segregation of activities, processed signals from the different brain regions need to be integrated. Evidence of this integration is found in that fact that the brain recognizes the words red and blue more quickly if they are written as red and blue than if they are written as red and blue, explains Hideaki Yamamoto of the AIMR at Tohoku University.

"Generally speaking, integration is when different neuronal groups activate coherently, whereas segregation is a state where the neuronal groups activate independently," says Yamamoto. "These two states of neural activation are well balanced in the brain and underpin its ability to carry out complex computation."

But it has not been clear how the brain coordinates these very different activities. "The neural basis of information processing in the brain is one of the biggest challenges in modern natural science," notes Yamamoto.

Now, Yamamoto, working with researchers at Tohoku University, the University of Barcelona, Tohoku Fukushi University, Waseda University and Yamagata University, has used a bottom-up approach to explore this problem. Specifically, they created a very simple model of a brain by linking four modules made up of circuits of rat neurons. The researchers then investigated how they integrate when they varied the degree of physical coupling between them (see image).

By varying the degree of physical coupling between four modules made up of circuits of rat neurons, AIMR researchers have mimicked the activity pattern that occurs in actual brains.

The team discovered that segregation and integration coexist only when there is almost no coupling between the four modules. If the coupling is any stronger, then integration predominates, whereas the modules operate independently of each other if it is weaker.

"By introducing modular organization to *in vitro* neuronal networks, we succeeded in suppressing excessive coherence between the networks and realized activity patterns that more closely resemble those observed in actual brains," says Ayumi Hirano-Iwata of the AIMR, who led the group. "While the observed dynamics are still far from the complexity in brains, we were able to gain insight into the fundamental mechanisms that shape brain dynamics."

In addition to demonstrating the advantages bestowed by the modular organization of the brain, the findings illustrate the power of using biophysical approaches to explore collective phenomena in complex systems.

1. Yamamoto, H., Moriya, S., Ide, K., Hayakawa, T., Akima, H., Sato, S., Kubota, S., Tanii, T., Niwano, M., Teller, S. *et al.* Impact of modular organization on dynamical richness in cortical networks. *Science Advances* **4**, eaau4914 (2018).

Crystal structure:

Fourth crystallographic phase uncovered

A new crystallographic phase found in metal oxides will force crystallographers to update their classification system for materials

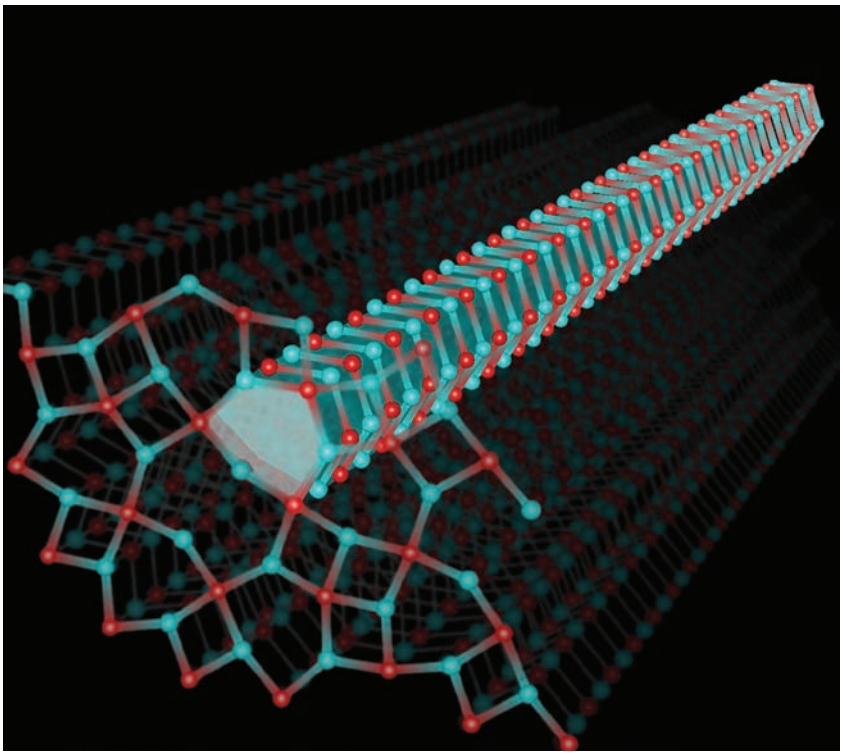
A previously unknown crystallographic phase has been discovered in ceramic metal oxides by a team of AIMR researchers[1]. This adds to the three other known phases and promises to lead to the development of new functional devices.

Not so long ago, solids were classified as either crystalline, with well-ordered, periodic structures, or amorphous, which lack any order. This neat, two-way classification scheme was disrupted by Dan Shechtman's discovery of quasicrystals in 1984, for which he was awarded the Nobel Prize in Chemistry in 2011. As their name suggests, quasicrystals are neither crystalline nor amorphous — they possess long-range order but are not periodic.

Now, with their discovery of a fourth crystallographic phase, Yuichi Ikuhara and his colleagues from the AIMR at Tohoku University have shown that the picture is more complicated yet.

The team discovered the new phase in thin films of two metal oxides, magnesium oxide (MgO) and neodymium oxide (Nd_2O_3), by using atomic-resolution scanning transmission electron microscopy. They subsequently confirmed it by performing theoretical calculations.

The researchers found the new crystallographic phase in samples made up of many small crystals of the metal oxides. Specifically, it occurred at the boundaries between two or more neighboring crystals. At these locations, the atoms have a random arrangement in two dimensions but possess translational symmetry in the third dimension, meaning that shifting the structure by a certain amount in that direction causes it to overlap with its original configuration (see image). Because of this one-dimensional (1D) order, Ikuhara's team refers to the phase as a 1D-ordered crystal.



The new crystallographic phase has a random arrangement in one plane, but translation symmetry along the direction perpendicular to the plane.

"It came as a surprise to us because no such structure had been reported for a simple oxide crystal such as magnesium oxide, which was thought to be either crystalline or amorphous," Ikuhara, the team leader, says.

This new crystallographic phase is more than a scientific curiosity — it alters the properties of the material. For example, crystalline magnesium oxide is an electrical insulator, but Ikuhara's team found that the 1D-ordered crystals of magnesium oxide are semiconducting. Ikuhara expects it will be possible to manipulate other material properties. "It should be possible to make ceramics less brittle, if we can fabricate bulk 1D-ordered crystals," he predicts.

The team has plans to further investigate the crystallographic phase. "We will study the mechanism by which 1D-ordered crystals form," Ikuhara explains. "We also want to find out how to make larger 1D-ordered crystals in order to fabricate novel functional devices."

1. Yin, D., Chen, C., Saito, M., Inoue, K. & Ikuhara, Y. Ceramic phases with one-dimensional long-range order. *Nature Materials* **18**, 19–23 (2019).

Spintronics:

Magnetic tunnel junctions go ferrimagnetic

A nano-thin layer of manganese is used to fabricate a magnetic tunnel junction with a high potential for magnetic storage devices

A solid-state structure that is promising for realizing extremely fast magnetic storage devices with ultralow power consumptions has been fabricated by AIMR researchers[1].

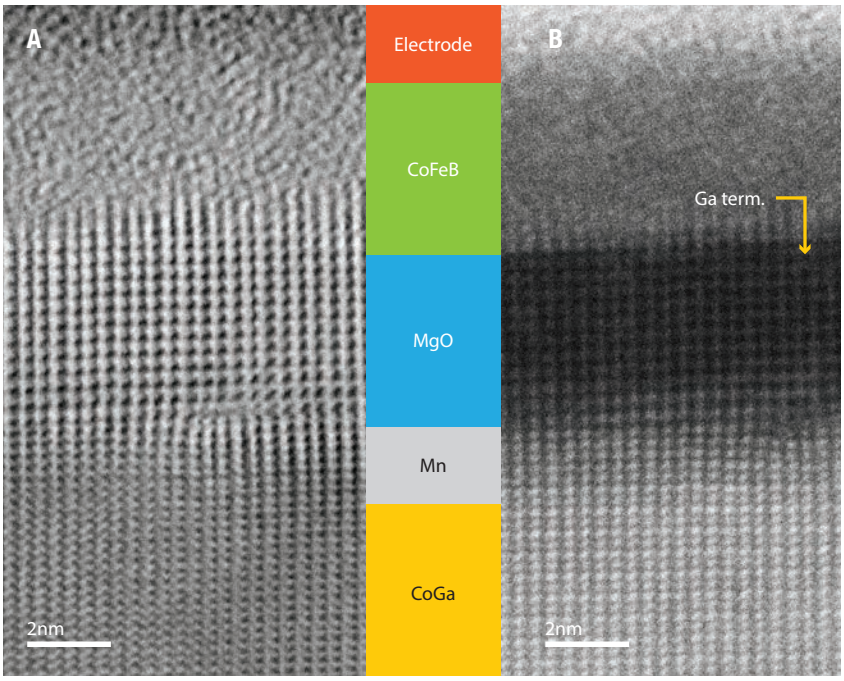
A magnetic tunnel junction consists of two magnetic layers separated by a non-magnetic, insulating layer. Information can be stored and erased by switching the relative magnetization of the two layers, which is usually done by an electric current flowing through the junction.

A faster, more efficient way to switch magnetization would be to vary the magnetic anisotropy, that is, the variation of magnetic properties of the structure with the direction of an applied magnetic field. Ideally, the magnetic anisotropy would be controlled by an electric voltage, but it has been difficult to find materials that exhibit voltage-controlled magnetic anisotropy.

Research efforts to date have focused on magnetic tunnel junctions based on ferromagnetic cobalt iron boron (CoFeB), but since ferromagnetic materials tend to generate large stray magnetic fields, they cannot be used to fabricate high-density integrated storage devices.

Now, Kazuya Suzuki of the AIMR at Tohoku University and his colleagues have used a new ferrimagnet, which generates negligible stray fields, to realize a magnetic tunnel junction that exhibits voltage-controlled magnetic anisotropy. They achieved this by including a very thin layer of manganese grown on cobalt gallium (CoGa) in the junction. Although manganese is anti-ferromagnetic or paramagnetic in bulk, their studies had shown that a nanolayer grown on cobalt gallium would be ferrimagnetic and possess perpendicular magnetic anisotropy.

The junction fabricated by Suzuki and co-workers included a manganese nanolayer grown on a cobalt gallium seed layer and capped by a magnesium oxide tunnel barrier and a magnetic cobalt–iron–boron layer (see image). Measurements of the electrical resistance through the structure when a magnetic field was applied parallel and perpendicular to the junction indicated that the manganese nanolayer possesses a large perpendicular magnetic anisotropy. Furthermore, the shape of resistance curves varied with the applied voltage. This shows that the structure exhibits voltage-controlled magnetic anisotropy, which is very likely due to the electric-field modulation of the electronic structure at the interface between the manganese and magnesium oxide.



A transmission electron microcopy image (A) and a high-angle annular dark-field scanning transmission electron microscopy image (B) of the cross-section of the junction.

The results could open a new line of research in magnetic tunnel junctions. "This concept might be widely used for other manganese-based nanolayers," says Suzuki. "We will do further research into other non-ferromagnetic manganese-based materials that convert to a perpendicular magnetized nanolayer. This research and concept will promote the development of new perpendicular magnetic materials for future spintronic storage devices."

1. Suzuki, K. Z., Kimura, S., Kubota, H. & Mizukami, S. Magnetic tunnel junctions with a nearly zero moment manganese nanolayer with perpendicular magnetic anisotropy. *ACS Applied Materials & Interfaces* **10**, 43305–43310 (2018).

Lithium batteries:

Electrode boosts storage capacity

A porous graphene material can store and release large amounts of lithium

A strong, porous material developed by AIMR researchers has the potential to dramatically increase the amount of energy lithium batteries can store[1], enabling more time between charging mobile devices.

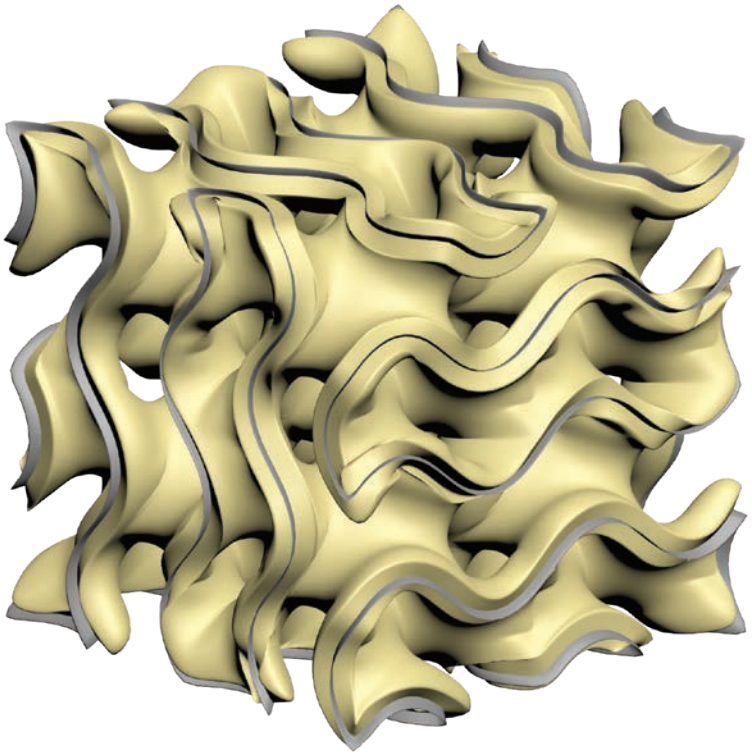
Rechargeable lithium-ion batteries are widely used to power electronic devices and electric vehicles. Lithium ions stored on their electrodes during charging are subsequently released during discharging. One of these electrodes, known as the anode, is typically made from graphite, an inexpensive form of carbon that is used in pencil lead. However, graphite accommodates a relatively small amount of lithium ions.

Anodes made from lithium metal have a much higher capacity, but they suffer from two problems. As lithium moves in and out of the anode, thin metal whiskers, called dendrites, start to sprout from it. The flow of lithium also causes the anode expand and contract. Both effects rapidly curb the battery's efficiency, and can even cause combustion.

A team led by Mingwei Chen of the AIMR at Tohoku University has now shown that anodes made from nanoporous graphene doped with nitrogen can host much more lithium than graphite. The material is also lightweight, flexible and highly conductive, making it promising as a battery anode.

The researchers grew the material inside a porous nickel template, before etching the metal away. Its porous structure gave nitrogen-doped graphene an extremely low density, enabling it to store large amounts of lithium without adding much weight to a battery. Its layered sheets of carbon atoms were peppered with nitrogen atoms, which helped to bind lithium.

After infusing the material's pores with lithium, the researchers found that the anode could undergo more than 700 charge–discharge cycles without any significant loss in performance, more than four times as many cycles as a pure lithium electrode. "I was really surprised by its ultrahigh stability," comments Gang Huang, a member of Chen's team.



Nanoporous nitrogen-doped graphene contains a very large surface area that helps it to store lithium.

Scanning electron microscope images revealed that dendrites did not grow on the anode, and its volume varied little on charging and discharging.

Furthermore, the charge storage capacity of the anode was a mere 10% lower than the theoretical maximum capacity of a pure lithium metal electrode. "The specific capacity of our nanoporous anode is nearly 10 times greater than the graphite electrodes typically used in lithium-ion batteries," notes Huang.

A battery containing the anode had a high charging rate and consistently outperformed a rival with a pure lithium anode. The researchers hope to apply the same anode design to other metal-electrode batteries, such as those using sodium or magnesium.

1. Huang, G., Han, J., Zhang, F., Wang, Z., Kashani, H., Watanabe, K. & Chen, M. Lithiophilic 3D nanoporous nitrogen-doped graphene for dendrite-free and ultrahigh-rate lithium-metal anodes. *Advanced Materials* **31**, 1805334 (2018).

Lithium batteries:

Complex hydride promising as solid electrolyte

A designed hydride has a combination of properties that make it nearly ideal as an electrolyte in all-solid-state lithium batteries

A new hydride developed by AIMR researchers could help finally realize all-solid-state lithium batteries[1]. This opens up a new direction for scientists to pursue in the race to develop better performing replacements for ubiquitous lithium-ion batteries.

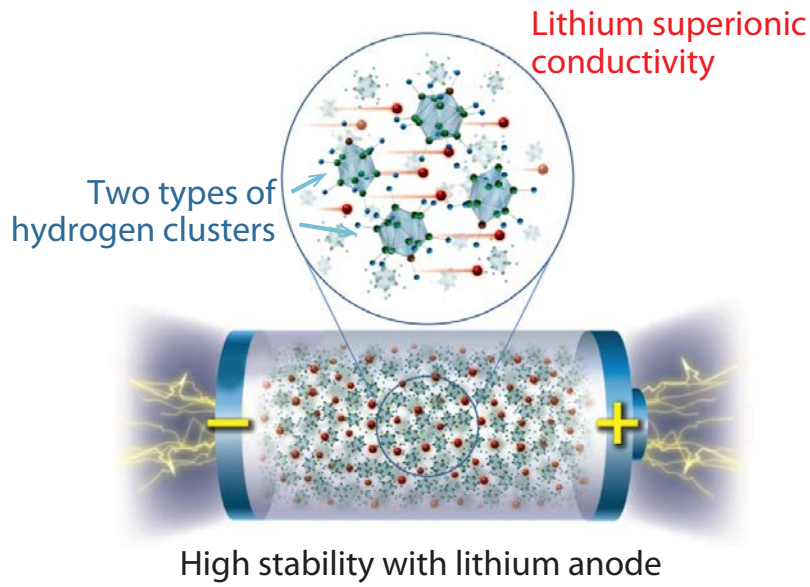
Lithium-ion batteries are used extensively to power everything from smartphones to electric vehicles. But they can suffer from several drawbacks, including low energy densities, leakage of the liquid electrolyte, and the potential to burst into flames. All three problems could be overcome by replacing the liquid electrolyte with a solid one.

Lithium metal is the material of choice for the anodes of such all-solid-state batteries, but existing solid electrolytes undergo unwanted side reactions with lithium, which increase the resistance between the anode and electrolyte. This in turn degrades battery performance after repeated charging and discharging.

Complex hydrides are inorganic compounds that consist of a positive metal ion and a molecular anion that contains hydrogen. While they do not undergo side reactions with lithium, they suffer from a low lithium ion conductivity.

Now, Sangryun Kim of the Institute for Materials Research (IMR) at Tohoku University, together with IMR and AIMR colleagues, has developed a complex hydride that combines both a high lithium conductivity and a good stability with lithium metal anodes, such that they do not react with them.

"This is the first time that complex hydrides have been shown to be suitable solid electrolytes for practical lithium-metal batteries," notes Kim. "To our surprise, we found that the resistance between our complex hydride and a lithium metal anode was almost negligible, meaning that lithium ions can freely move between the anode and electrolyte with scarcely any barrier."



A complex hydride that has two types of hydrogen clusters exhibits both a high lithium ion conductivity and an excellent stability with lithium metal anodes.

The researchers developed the complex hydride by tailoring the structures of its hydrogen clusters. The complex hydride consists of a mixture of two types of anions (see image): 70% of anions contain one carbon atom and nine boron atoms (as in $(CB_9H_{10})^-$), while 30% contain one carbon atom and eleven boron atoms (as in $(CB_{11}H_{12})^-$).

"This material is a totally new kind of solid electrolyte," says Kim. "We hope our results will inspire future efforts to find lithium superionic conductors based on complex hydrides and also open up a new trend in solid electrolyte materials, which may lead to the development of high-energy-density electrochemical devices."

The team intends to further improve their electrolyte. "There are many other complex anions that we can investigate," comments Kim. "Taking the present work as the first step, we intend to conduct systematic studies to produce complex hydrides that have even better lithium ion conductivity and stability with lithium metal anodes."

1. Kim, S., Oguchi, H., Toyama, N., Sato, T., Takagi, S., Otomo, T., Arunkumar, D., Kuwata, N., Kawamura, J. & Orimo, S. A complex hydride lithium superionic conductor for high-energy-density all-solid-state lithium metal batteries. *Nature Communications* **10**, 1081 (2019).

Topological phases:

Two new fermions discovered

Two fermions have been found that can exist only as quasiparticles inside topological crystals

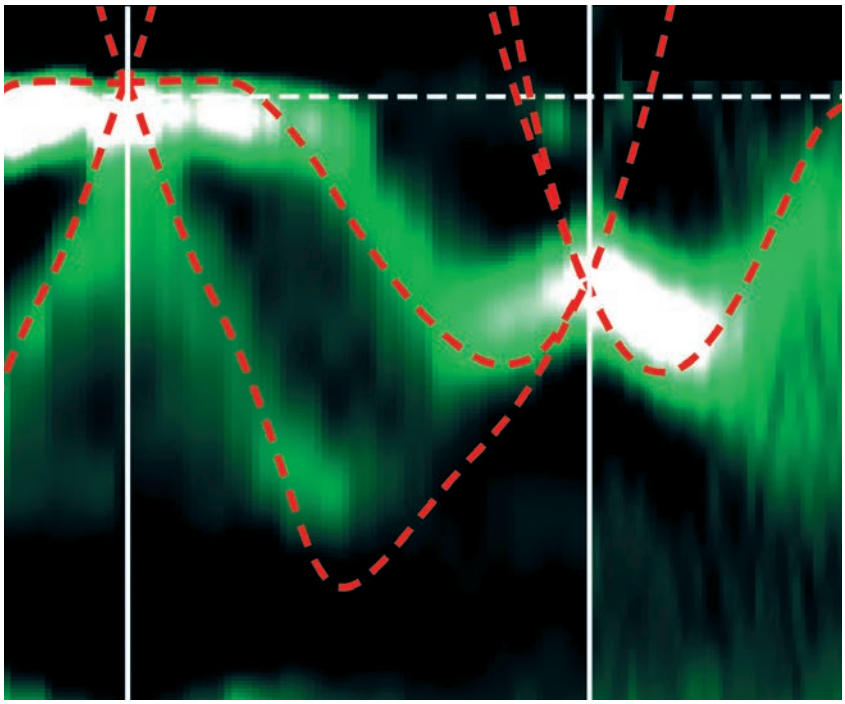
Two new fermions have been found in a topological material by AIMR researchers[1]. This is remarkable because, unlike 'quasiparticle' fermions previously discovered in material systems, these two quasiparticle fermions lack particle counterparts that can exist in a vacuum.

Particles with an integer spin are classified as bosons, whereas particles with a half-integer spin are called fermions. The best known example of a fermion is the electron, which has a spin of one half.

According to quantum field theory, fermions in a vacuum can be further classified into three types: Dirac, Weyl or Majorana fermions. Of these, only Dirac fermions have been observed as particles in high-energy physics experiments performed at massive particle accelerators such as CERN's Large Hadron Collider. But Dirac and Weyl fermions also been found as quasiparticles — collective excitations of electrons that behave as particles — in topological materials, exotic systems whose surface properties differ greatly from their bulk properties.

Now, Takafumi Sato of the AIMR at Tohoku University and his co-workers have found two new fermion quasiparticles that do not fit into any of the three categories. They discovered these fermions in cobalt silicide (CoSi) by using synchrotron radiation to probe the energy levels of electrons in the material.

"Our discovery is exciting because it adds a new category of fermionic quasiparticles to the well-known Dirac and Weyl fermions," explains Sato. "We anticipate it will stimulate the search for new types of fermionic quasiparticles in a wider variety of topological materials using synchrotron radiation."



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An angle-resolved photoemission spectrum that reveals the existence of one of the two new kinds of fermions discovered in cobalt silicide.

The researchers were inspired to search for the fermions by a theoretical prediction published two years ago that materials such as cobalt silicide with a chiral crystal structure will harbor such fermions. The specific point-group symmetry of these crystals permits them to host fermions that cannot exist in the higher symmetry of free space.

Sato notes that it was challenging to prepare samples of CoSi that were clean and flat enough to analyze. "We cleaved millimeter-sized bulk CoSi crystals more than 50 times," he recalls. "In just a few cases, we were able to obtain a sufficiently flat surface in a very narrow region of about 100 by 100 micrometers."

The discovery could lead to practical applications in the future. "While it's still early days, this finding could pave the way toward realizing next-generation electronic devices that utilize new fermions," notes Sato. "They may be useful for high-speed devices because nodal fermions generally have high mobilities, and their chirality might make them applicable to some opto- and magneto-electronic devices."

1. Takane, D., Wang, Z., Souma, S., Nakayama, K., Nakamura, T., Oinuma, H., Nakata, Y., Iwasawa, H., Cacho, C., Kim, T. *et al.* Observation of chiral fermions with a large topological charge and associated Fermi-arc surface states in CoSi. *Physical Review Letters* **122**, 076402 (2019).

Nanoporous graphene:

High strength and flexibility achieved

Excellent tensile strength and ductility have been realized in an ultralight, three-dimensional structure made of nanoporous graphene

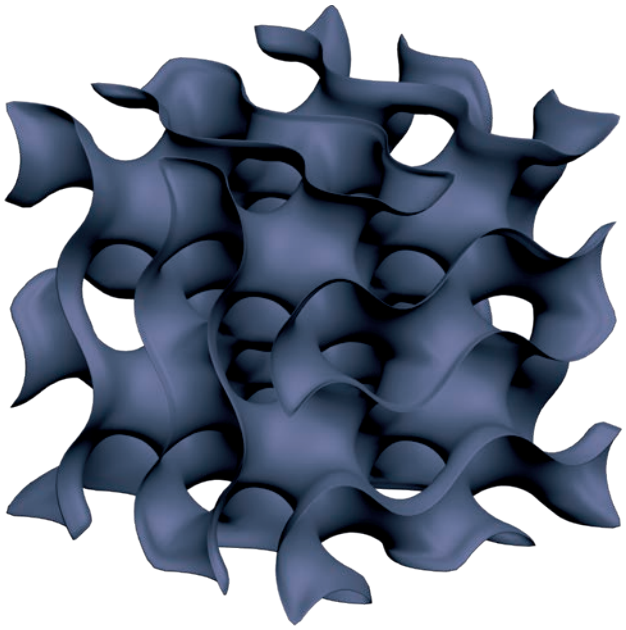
An ultralight, graphene-based material that is both extremely strong and ductile has been developed by AIMR researchers[1]. These properties make the material promising for a wide range of applications, including those in the aerospace and automotive industries.

Graphene's strength is well documented — the flat sheet of carbon atoms arranged in a hexagonal honeycomb lattice is one of the strongest materials discovered to date, hundreds of times stronger than steel. But it has been challenging to use graphene's two-dimensional strength to form strong three-dimensional structures, particularly those that can withstand tension (forces that seek to pull the structures apart), because graphene's strength is reduced if it contains any defects. In addition, adjacent graphene sheets are held together by weak Van-der-Waal bonds.

Furthermore, it has been difficult to realize lightweight, carbon-based materials that are both strong and ductile.

Now, inspired by the structures of recently developed artificial materials known as metamaterials, Hamzeh Kashani and Mingwei Chen of the AIMR at Tohoku University and their colleagues have made an ultralight graphene structure containing nanoscale pores that has an excellent tensile strength and ductility.

"Metamaterials are artificially engineered structures on the microscale or nanoscale whose unique properties stem mainly from their structure rather than the properties of their constituent materials," says Kashani. "By using this concept and employing a bicontinuous, nanoscale architecture, we were able to shape a single sheet of graphene into a three-dimensional structure."



This nanoporous, graphene-based structure has both high tensile strength and ductility.

The team produced centimeter-sized pieces of the material by growing graphene on a nickel block that contained nanosized pores. They then stripped away the nickel by etching, so that only a three-dimensional seamless tubular network of graphene remained (see image).

The secret to the material's simultaneous strength and flexibility lies in the fact that the graphene structural elements can both stretch with an extremely high in-plane strength and bend with out-of-plane flexibility. "Lightweight porous structures that deform with stretching-dominated modes show higher strength and stiffness, whereas those with bending-dominated modes have lower strength and stiffness but offer more flexibility and ductility," explains Kashani. "Our material can respond to loads in entirely new ways through a combination of stretching and bending deformation modes."

The results have broader implications for two-dimensional materials besides graphene. "Our work demonstrates that the two-dimensional properties of materials can be exploited by judicious design of the architecture of three-dimensional nanostructures," says Kashani.

The team now intends to improve the physical and mechanical properties of composite materials by using their graphene material to reinforce metal and polymer matrices.

1. Kashani, H., Ito, Y., Han, J., Liu, P. & Chen, M. Extraordinary tensile strength and ductility of scalable nanoporous graphene. *Science Advances* **5**, eaat6951 (2019).

Topological insulators:

Imaging nanoscale domains on a multilayer structure

A nanoscale beam allowed the surface of a multilayer topological structure to be imaged for the first time

The mosaic surface of a multilayer structure made up of two materials with different topological properties has been imaged at a nanoscale resolution by AIMR researchers[1]. As well as providing important insights into the heterostructure, their results demonstrate the power of the nanoscale-resolution spectroscopy technique they used.

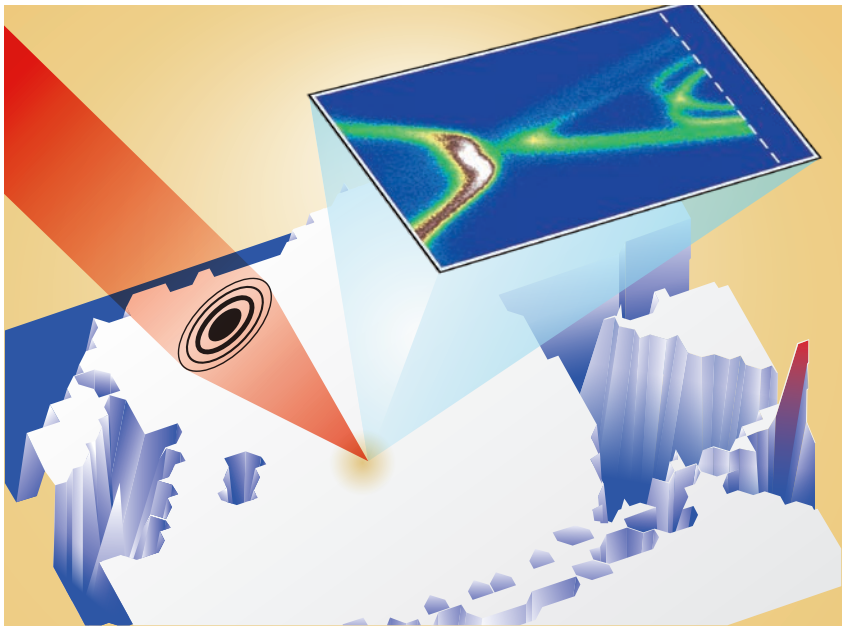
Exotic materials known as topological insulators have been attracting a lot of interest since their discovery a decade ago. Because of their topological properties, electric currents can flow on their surfaces but not inside them.

While blocks or thin films of topological insulators have been the main focus of research, structures made up of alternating layers of topological insulators and other materials are beginning to be explored. They have the advantage that their properties can be tuned by varying parameters like the thickness and stacking sequence of the layers.

"Such wide tunability is very useful for realizing novel topological phenomena," notes Takafumi Sato of the AIMR at Tohoku University. "For example, inserting superconducting or magnetic layers into a crystal may realize topological superconductivity or the magnetoelectric effect, respectively."

One useful technique for examining how the structural parameters of such multilayered structures affect the electrical properties of their surfaces is angle-resolved photoemission spectroscopy (ARPES). However, the beam of a conventional ARPES system is far too large to resolve the nanoscale variation in surface properties.

To overcome this, Sato and his co-workers at Tohoku University's Department of Physics and elsewhere used a nano-ARPES system that has a beam size of about 120 nanometers — more than 800 times smaller than that of a conventional system — to probe the surface of a topological heterostructure made up of layers of lead selenide, a normal insulator alternating with layers of bismuth selenide, a topological insulator.



By using angle-resolved photoemission spectroscopy (ARPES) with a nanoscale beam (red 'pencil' on left), researchers at AIMR were able to image the domains on a multilayer topological heterostructure and determine their electronic states (blue ARPES intensity plot).

They were able to directly observe nanoscale domains on the surface of the heterostructure and determine their size, shape and distribution. Furthermore, the researchers could determine the electronic state of each domain and find out how the domains varied with the thickness of the topological insulator layers within a sample.

To conduct their experiments, the researchers traveled to France to use one of only about three nano-ARPES systems in the world. But in a few years they will be able to use a new synchrotron that is being constructed at Tohoku University.

And by using an even higher resolution nano-ARPES system, they hope to be able to resolve the boundary between different domains, which may host topological edge states that exhibit peculiar properties. "Nobody has ever observed this edge state directly by ARPES," says Sato.

1. Nakayama, K., Souma, S., Trang, C. X., Takane, D., Chen, C., Avila, J., Takahashi, T., Sasaki, S., Segawa, K., Asensio, M. C. *et al.* Nanomosaic of topological Dirac states on the surface of $Pb_5Bi_{24}Se_{41}$ observed by nano-ARPES. *Nano Letters* **19**, 3737–3742 (2019).

Electrochemical water splitting:

Mathematically designed graphene on edge

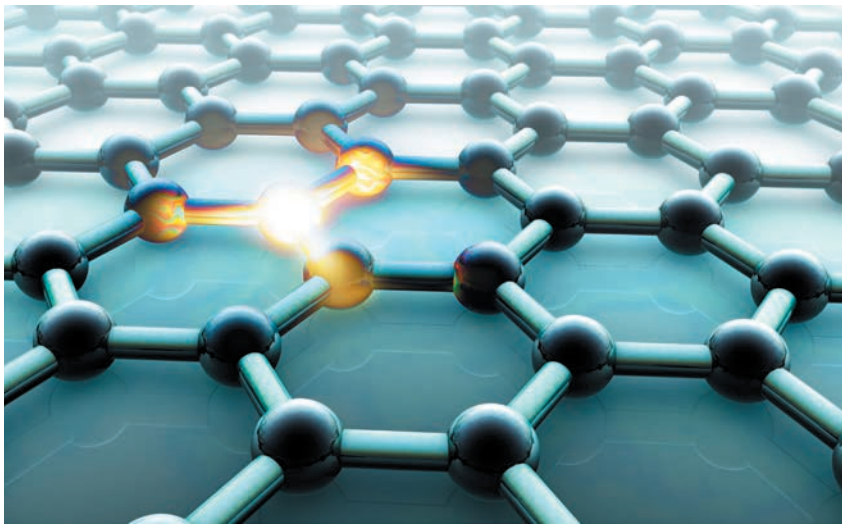
Holey sheets of chemically doped graphene have great potential for generating clean hydrogen fuel

Mathematically optimized graphene-based structures containing the right combination of nitrogen and phosphorus atoms could match — or even outperform — expensive platinum catalysts for producing hydrogen, an AIMR co-led team has shown[1]. This could make hydrogen production cheaper and thereby facilitate the widespread adoption of hydrogen in place of fossil fuels.

Platinum is currently the material of choice for catalyzing the hydrogen evolution reaction (HER). In this process, renewable electricity from solar panels or wind turbines is used to electrolyze water, releasing clean hydrogen, which can be stored, transported and used as a fuel. When hydrogen is burned, water vapor is the only emission.

However, because platinum is rare, electrocatalysts made from cheap, abundant carbon — in the form of single-atom-thick sheets called graphene — are being investigated. Graphene's HER activity is affected by various factors, including chemical dopants and atomic defect structures such as those around holes in the graphene sheet, says Akichika Kumatani of the AIMR at Tohoku University. "However, there's no direct evidence as to which factors — atomic structures, chemical dopants or both — give the highest performance," he explains.

To answer that question, the researchers designed atomic structures of graphene mathematically and then produced the structures using chemical vapor deposition with silicon dioxide nanoparticles. They also developed scanning electrochemical cell microscopy (SECCM) for characterizing the graphene structures. It essentially enabled them to recreate an electrochemical cell inside a scanning microscope, so that they could measure the HER at different points across the graphene surface with a high spatial resolution.



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Introducing defects and chemical dopants can boost the electrocatalytic activity of graphene for the hydrogen evolution reaction.

Using SECCM, the team compared the HER performance of graphene with and without holes, and with and without nitrogen and phosphorus dopant atoms. They found that the most catalytically active sites were areas of doped graphene around the edges of holes. The graphene around the holes has the greatest concentration of defects in the carbon lattice, which can accommodate many dopant atoms in close proximity.

Computational studies gave further insights. The most catalytically active sites were nitrogen atoms in a 'pyridinic' bonding arrangement with surrounding carbon atoms, especially if they were co-located with phosphorus atoms, which enhanced the charge on the pyridinic nitrogen, further boosting catalytic activity.

"Remarkably, our theoretical results suggested that the optimal structure beats platinum's performance for water electrolysis," Kumatani says. "Importantly, the atom structure was inspired by mathematical analysis. We believe this carbon-based structure for HER can be essential for developing a sustainable hydrogen economy."

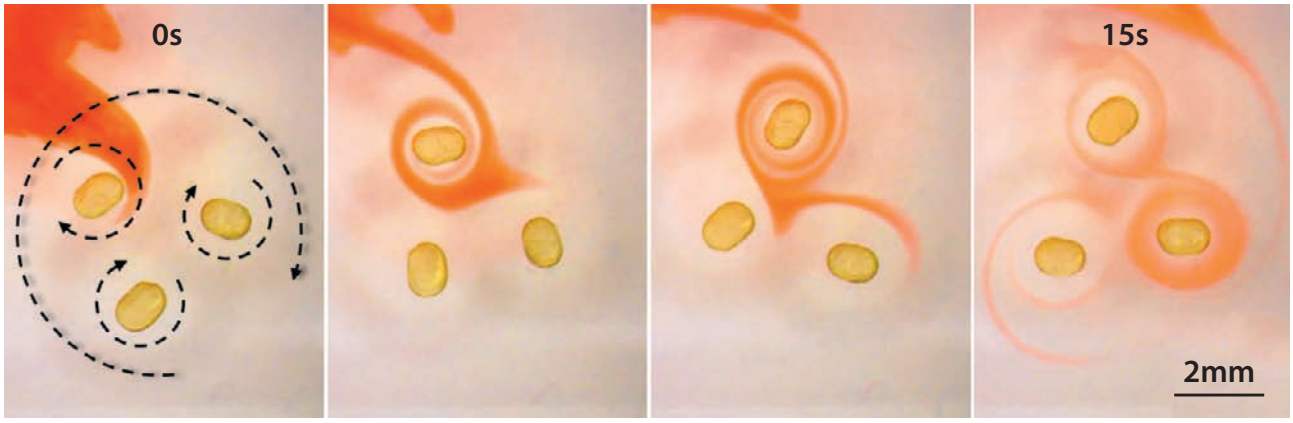
The team plans to optimize methods for creating graphene with more holey edges with chemical dopants, as well as to use SECCM to study other important electrochemical reactions such as carbon dioxide reduction.

1. Kumatani, A., Miura, C., Kuramochi, H., Ohto, T., Wakisaka, M., Nagata, Y., Ida, H., Takahashi, Y., Hu, K., Jeong, S. *et al.* Chemical dopants on edge of holey graphene accelerate electrochemical hydrogen evolution reaction. *Advanced Science* **6**, 1900119 (2019).

Magnetic materials:

A magnet that can twist and turn

Liquid droplets containing nanoparticles can have permanent magnetism



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Three liquid droplets that have a permanent magnetization can be made to rotate in unison by applying a rotating magnetic field. The orange dye shows the swirling fluid flow created by the rotating droplets.

A liquid that is a permanent magnet has been developed for the first time by an AIMR-led team[1]. In the future, it could be used for various applications, such as actuators in liquid robotic systems.

Liquids that become magnetic when placed inside a magnetic field have been known since the 1960s, when NASA scientists investigated their potential use as rocket fuel. However, as soon as the magnetic field is switched off, these liquids rapidly lose their magnetism due to the thermal motion of magnetic particles. Until now, the only known permanent magnets were solids.

Now, Tom Russell of the AIMR at Tohoku University and his collaborators in the USA and China have succeeded in making small liquid droplets that behave similarly to solid permanent magnets, but retain liquid characteristics.

The team used a modified three-dimensional printer to inject millimeter-sized water droplets containing iron oxide nanoparticles into an oil containing a surfactant. The nanoparticles congregated near the surfaces of the droplets, forming shell-like structures. When a magnetic field was applied, the nanoparticles became magnetized. But to the team's surprise, the droplets retained some of this magnetization even when the magnetic field was turned off.

The researchers demonstrated their liquid magnets in various ways. For example, they made several of them rotate in unison by applying a rotating magnetic field (see image). Furthermore, by drawing a spherical droplet into a narrow tube so that it became cylindrical, the team showed that the droplets remained magnetic even on changing their shape. The magnetization remained even when a droplet was broken up into hundreds of smaller droplets, effectively forming multiple permanent magnets.

The magnetic droplets are much more than a scientific curiosity; they have various exciting applications. "Conventional solid magnets have made great contributions to the development of modern industry," says Russell. "But what if magnets were soft, flowable and reconfigurable like a liquid? Magnets that could conform to spatial constraints? The reconfigurable ferromagnetic liquid droplets we have uncovered represent a milestone for the further development of magnetic materials. These amazing liquid magnetic materials will attract attention in biology, physics and chemistry."

Since the researchers are uncertain about how their liquid retains its magnetism, discovering the mechanism is a major priority. "We do not understand the exact coupling since the length scales between the particles is too large for dipolar coupling," says Russell. "And so we're currently investigating the exact origin of the coupling."

1. Liu, X., Kent, N., Ceballos, A., Streubel, R., Jiang, Y., Chai, Y., Kim, P. Y., Forth, J., Hellman, F., Shi, S. *et al.* Reconfigurable ferromagnetic liquid droplets. *Science* **365**, 264–267 (2019).

Metallic glasses:

Discovering better combinations faster

A new and powerful method for accelerating the optimization of metallic glasses has been demonstrated

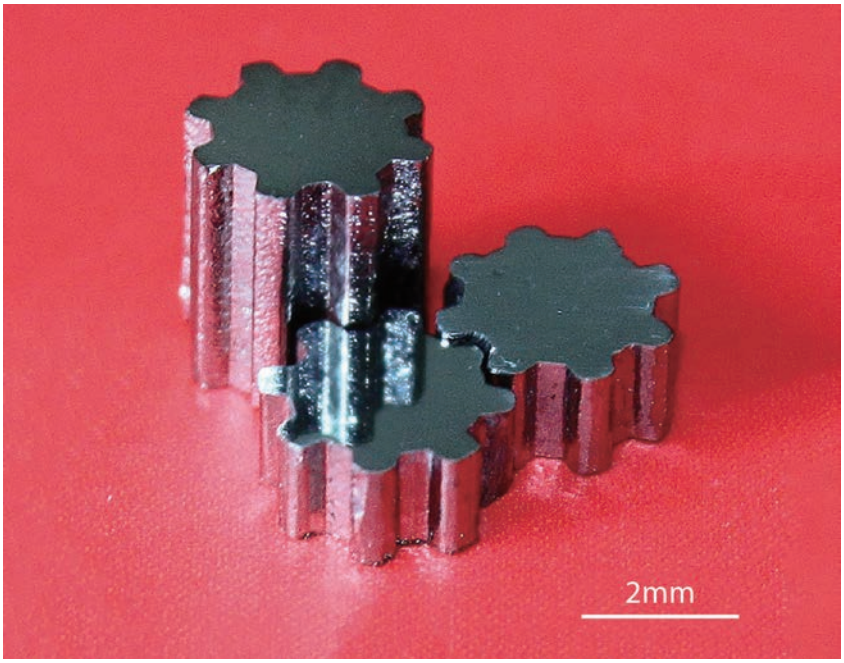
A rapid approach for making and testing metallic glasses has been developed by AIMR researchers[1]. This method promises to greatly speed up the search for optimized metallic glasses.

First discovered in 1960, metallic glasses are metal alloys that have an amorphous, glass-like structure rather than a crystalline structure like conventional alloys. They have many useful properties, including high processability, high strength, and resistance to wear and corrosion.

For metallic glasses to be useful for applications such as electronic components and biomedical implants they need to maintain this glass-like state over a wide temperature range. "Generally, metallic glass with a wide supercooled liquid region can be fabricated into large samples and easily shaped into different structures, which is good for commercial applications," explains Zhen Lu of the AIMR at Tohoku University. They also need a high glass-transition temperature — the point at which they change from a glass to a supercooled liquid — to ensure that they have a good thermal stability and a high stiffness. However, finding metallic glasses that satisfy these two criteria through trial and error is painstakingly slow.

Now, Lu and collaborators at the Institute of Physics (Chinese Academy of Sciences) and other institutions in China and the United States have come up with a fast method for making and measuring metallic alloys made up of different proportions of three metals, and have used it to find a metallic glass with a high glass-transition temperature of 1,162 kelvin.

The team sputtered three metals — iridium, nickel and tantalum — onto a substrate, the proportions of which varied continuously with position on the substrate.



The mechanical properties of metallic glasses make them suitable for small components such as microgears.

They then measured the electrical resistivity at different points on the substrate. As resistivity correlates to glass-forming ability, the researchers were able to quickly and easily identify regions where metallic glasses had formed. They also tested the mechanical properties at different substrate locations.

"By combining a high-throughput fabrication method such as magnetron co-sputtering with high-throughput measurements, we can explore a library of samples containing hundreds of components and properties in just a few days," says Lu. "This approach promises to greatly accelerate the development rate and extend the exploration range of new materials."

The method is straightforward to implement. "Unlike previous approaches, it can be directly used for many glass-forming systems," says Lu. "It costs about US$3,000 to build the apparatus we used for mapping electrical resistance, making it feasible and affordable for many laboratories that lack access to a synchrotron."

The team wants to apply their method to other metal combinations. "We plan to use these high-throughput combinatorial methods to explore new libraries of metallic glasses and extend the applications of metallic glasses," says Lu.

1. Li, M.-X., Zhao, S.-F., Lu, Z., Hirata, A., Wen, P., Bai, H.-Y., Chen, M., Schroers, J. Liu, Y. & Wang, W.-H. High-temperature bulk metallic glasses developed by combinatorial methods. *Nature* **569**, 99–103 (2019).

Fuel-cell catalysts:

Surpassing platinum

Inexpensive catalysts can exceed the performance of those containing platinum

A new class of platinum-free catalysts that could lead to cheaper fuel cells has been designed by researchers at the AIMR[1]. These catalysts have catalytic activities that surpass those of even ones containing platinum, and can be produced under mild conditions at low cost.

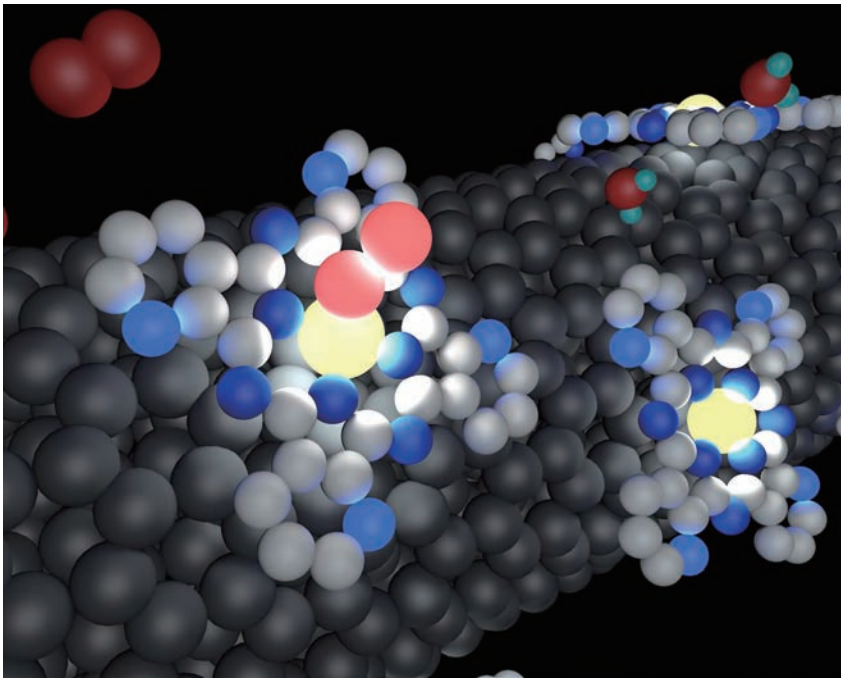
Hydrogen fuel cells, which generate electricity by reacting hydrogen and oxygen to produce water, are highly attractive clean power sources for electric vehicles and domestic appliances. But one obstacle for their commercial adoption has been the fact that the most effective catalysts for the oxygen-splitting reaction that occurs on their cathodes are expensive because they contain the precious metal platinum. The same problem arises in metal–air batteries.

With a view to reducing the cost of fuel cells, material scientists have been searching for stable platinum-free catalysts that have high catalytic activities.

Now, Hiroshi Yabu and Hiroya Abe at the AIMR at Tohoku University and their coworkers have developed catalysts that tick all the boxes — they are made from low-cost materials, are easy to make, have a high catalytic activity, and show good stability.

The team made the catalysts by coating multiwalled carbon nanotubes with a single layer of molecules of iron azaphthalocyanines, complexes consisting of an iron atom surrounded by four interconnected aromatic rings.

The researchers had not expected their catalysts to be as effective. "We were surprised that we could realize a catalytic activity superior to that of platinum-based catalysts by just swapping the peripheral benzene groups of phthalocyanine with pyridine groups and adsorbing this compound on carbon nanotubes," notes Yabu. "Indeed, as far as we're aware, this is the highest activity obtained for conventional catalysts based on modified carbon nanotubes." The researchers found that this high activity is due to the favorable positioning of nitrogen atoms in the azaphthalocyanine rings.



A schematic drawing showing the atomic structure of a new catalyst whose catalytic activity is higher than that of platinum-containing catalysts (gray spheres: carbon atoms in carbon nanotubes; yellow spheres: iron atoms; blue spheres: nitrogen atoms; white atoms: carbon atoms in azaphthalocyanine rings; red spheres: oxygen atoms; green spheres: hydrogen atoms).

The catalysts have the added advantage that, unlike other platinum-free catalysts, they do not require high temperatures to manufacture. "Our phthalocyanine derivative dissolves in organic solvents and is easily absorbed onto the carbon nanotubes," says Yabu. "This is a great advantage compared with catalysts made by pyrolysis, which require complex, high-temperature processes and good control of the process conditions."

The team has established a new company to supply the catalysts worldwide. Furthermore, they are performing theoretical calculations to try to find other phthalocyanine derivatives that have even higher catalytic activities. "We believe this kind of collaboration, involving both theory and experiment, will lead to the development of many more highly functional materials," says Yabu.

1. Abe, H., Hirai, Y., Ikeda, S., Matsuo, Y., Matsuyama, H., Nakamura, J., Matsue, T. & Yabu, H. Fe azaphthalocyanine unimolecular layers (Fe AzULs) on carbon nanotubes for realizing highly active oxygen reduction reaction (ORR) catalytic electrodes. *NPG Asia Materials* **11**, 57 (2019).

Iron-based superconductors:

Ruling out a cause for high-temperature superconductivity

Measurements on a sister system eliminate a popular explanation for the high-temperature superconductivity of iron selenide monolayers

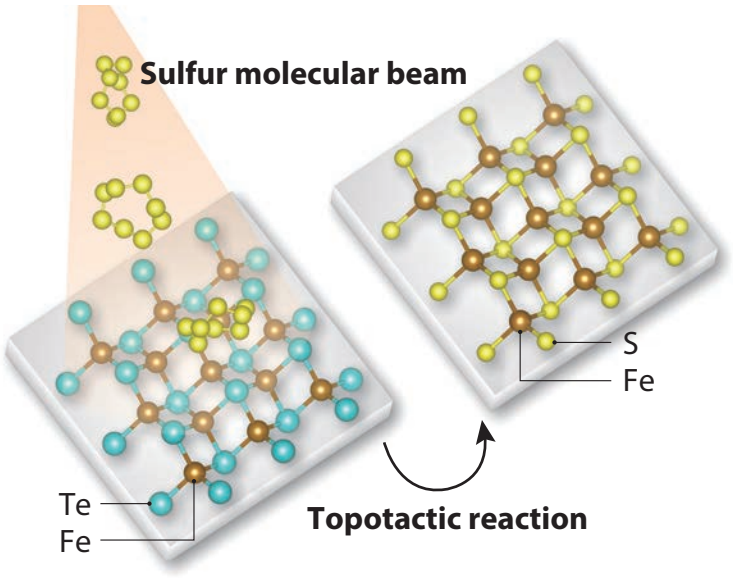
Flying in the face of expectations, the high-temperature superconductivity of a single-atomic layer of iron selenide on strontium titanate cannot be explained solely by coupling between electrons and sound waves, experimentalists at AIMR have shown[1]. This finding will force material scientists to re-evaluate the origin of the system's superconductivity.

The system consisting of a monolayer of iron selenide (FeSe) on a strontium titanate ($SrTiO_3$) substrate caused a stir in 2012 when it was found to superconduct at the high temperature of 65 kelvin, making it the iron-based superconductor with the highest transition temperature.

It is also anomalous in that almost all high-temperature superconductors lose their high-temperature superconductivity when they are made into monolayer films, whereas the transition temperature of iron selenide actually increases from 8 kelvin for a block of the material to 65 kelvin for a single-atom layer.

There has been a lot of discussion about what is responsible for the superconductivity of monolayer iron selenide on strontium titanate. A popular explanation is that coupling between electrons in the monolayer and sound waves (phonons) in the substrate alone generates the superconductivity.

Now, by performing measurements on a sister system to iron selenide, Takafumi Sato at the AIMR at Tohoku University, Kosuke Nakayama at Tohoku University, and their co-workers, have demonstrated that this mechanism can be ruled out. They did this by growing a single-atom film of iron sulphide (FeS) on strontium titanate and revealing that, while it had the same crystal structure as iron selenide and strong electron–phonon coupling, it did not exhibit high-temperature superconductivity.



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Takafumi Sato and his team produced a monolayer of iron sulphide for the first time by using molecular-beam epitaxy to deposit sulfur atoms on a monolayer of iron telluride (left image) and then inducing a topotactic reaction to replace the tellurium atoms in the monolayer with sulfur atoms.

This finding came as a surprise to the team. "We were so sure that electron–phonon coupling was essential for high-temperature superconductivity in iron selenide that when we observed it in monolayer iron sulphide we felt almost certain that we had made a new high-temperature superconductor," recalls Sato. He notes that while the measurement shows that electron–phonon coupling is not solely responsible for the superconductivity, the coupling may still contribute to it.

Until now no-one had succeeded in growing a monolayer of iron sulphide. To achieve that, the team developed a new fabrication method that involved first depositing sulfur atoms on a monolayer of iron telluride (see image). They then induced a reaction that effectively swapped the tellurium atoms with sulfur atoms. This fabrication method is promising for making other novel functional materials such as metal dichalcogenides and topological systems.

The team suspects that strong correlations between electrons in the iron selenide monolayer may be responsible for its superconductivity, and they are now doing experiments to test this hunch.

1. Shigekawa, K., Nakayama, K., Kuno, M., Phan, G. N., Owada, K., Sugawara, K., Takahashi, T. & Sato, T. Dichotomy of superconductivity between monolayer FeS and FeSe. *Proceedings of the National Academy of Sciences USA* **116**, 24470–24474 (2019).

IN THE SPOTLIGHT

The AIMR has grown rapidly since its inauguration in 2007. It now boasts about 100 leading researchers from all over the world, including 25 internationally renowned principal investigators who are charged with pioneering new and innovative breakthroughs in materials science. The institute is also active in developing young, promising researchers with a focus on strong cross-disciplinary collaboration and creativity. AIM*Research* spotlights these talented researchers of the present and future, detailing their daily research activities and scientific ambitions.

INTERNATIONAL SYMPOSIUM

Published online on 25 March 2019

Seeking synergies between fields and countries

A gathering of innovative scientists sparked lively discussions on the future of materials science and spintronics

Over 250 researchers attended the three-day symposium.

Tohoku University's selection as a Designated National University by the Japanese government in 2017 is spurring efforts to build up world-class research capabilities in four of its strongest fields: materials science, spintronics, next-generation medical care, and disaster science. As a continuation of the inaugural 2018 symposium that celebrated new beginnings in two of these fields, materials science and spintronics, the Second Symposium for World Leading Research Centers was held in Sendai on 16–18 February 2019.

The meeting gave more than 250 researchers from Japan and around the world a valuable opportunity to exchange ideas about topics as wide ranging as structural materials, electronic materials, biomaterials, energy materials, mathematics and informatics. A recurring theme of the symposium was the importance of collaboration that transcends disciplinary and national borders.

The importance of multidisciplinary, collaborative research

In his opening remarks, Hideo Ohno, a renowned physicist and the president of Tohoku University, noted that many of history's greatest scientific achievements were realized through collaboration. By way of example, he described Tohoku University's outstanding contributions in the field of magnetism, from the pioneering work of Kotaro Honda more than a century ago to Masato Sagawa's recent invention of the strongest magnets. Ohno expressed his hope that collaborative efforts between disciplines will continue to build on such successes.

Motoko Kotani, director of the AIMR at the time, shared further examples of the university's breakthroughs in materials research, computer science and engineering. She explained how Tohoku University is adopting a multilayer approach to establish an ecosystem designed to strengthen

research activities not only at the new materials science center but also across the university's core research clusters.

"More than 400 researchers are now working on materials science at Tohoku University," she said. "And synergy is the key to building successful interdisciplinary research alliances with a global reach."

As the leader of the spintronics research center, Yoshiro Hirayama, professor at Tohoku University's Department of Physics, explained how activities at the Center for Science and Innovation in Spintronics and its core research cluster are "laying technological foundations for next-generation Internet of Things (IoT) applications." He also spoke of the key partnership between Tohoku University and Tsinghua University as a springboard for more developments in spintronics and topological materials.

Qi-Kun Xue, a professor and vice-president of Tsinghua University in Beijing, China, and a principal investigator at the AIMR, stressed the importance of materials science and spintronics research for realizing sustainable development. The close collaborations between Tsinghua University and Tohoku University nurtured over more than 20 years, he said, will continue to encourage joint research in these critical fields.

From glazed pottery to ultrafast memory devices

The first of two plenary speakers was Alan Lindsay Greer, a professor of materials science at the University of Cambridge and a long-time collaborator and principal investigator at the AIMR. He outlined developments in crystallization studies on different kinds of glass-forming systems such as polymers, chalcogenides, metals and alloys. Greer described a remarkable range of crystal growth rates correlated with thermodynamic and kinetic parameters — of fundamental interest as well as of potential importance for developing ultrafast computing systems. "Studies of fast crystallization are relevant for computer memory, and may point to the application of metals for fast phase change," he said.

Alan Lindsay Greer talks about the potential of studying the crystallization of various glass-forming systems.

Greer then reflected on the question of whether pure metals could be considered glass formers, despite previous assumptions to the contrary. "It seems we can, and this may even be exploitable," he said, describing the concept of liquid fragility, and how a possible crossover from fragile to strong liquid behavior on cooling could be a vital part of understanding fast crystal growth. "The ancients knew about this property of glasses, as it turns out to be highly relevant to glass blowing," Greer noted. "And this fragile-to-strong crossover may be important for the performance of memory devices."

Sharing images of nineteenth-century glazed pottery from France and Japan, Greer gave other examples of what can be achieved by phase transformation. The ring patterns in these artworks, he explained, indicate where the potter has changed the temperature of the furnace, and are subject to a considerable degree of control. Greer drew parallels between these patterns and the nanoscale spiral patterns produced by an intriguing phenomenon known as explosive crystallization in amorphous thin films. Much still remains to be explored, Greer suggested, in designing and optimizing materials for phase-change applications.

The next step for quantum computing

In a talk titled 'Why should we care about topological quantum computer?', Kang Wang of the University of California, Los Angeles, spoke about the exciting possibilities that would be opened up by quantum computing devices to solve problems that go far beyond the limits of classical computers. There is great potential in drug discovery, techniques for analyzing the whole body, smart traffic management, earthquake disaster prevention, and even the ability to count the number of atoms in the observable universe.

Today's computers are based on a binary system that uses zeros and ones and operates in a sequential mode. In contrast, quantum computers "offer a drastically different way of computing in massive parallelism using quantum bits (qubits), which are superimposed or entangled, such that one and zero can no longer be considered independent states," Wang explained. "However, the superposition and entanglement need to maintain phase

coherence, which is the key challenge for realizing quantum computing and scaling up the number of qubits."

Wang described how his group has discovered a new direction for realizing robust topological quantum computing that overcomes the challenge of decoherence. They have found firm evidence for the existence of the elusive Majorana fermion — a particle that is its own antiparticle, which was theoretically predicted by Ettore Majorana in 1937. "Majorana particles could be used as topological qubits to realize robust topological quantum computing," Wang said.

Kang Wang is excited about the potential of quantum computing.

The poster session gave researchers the opportunity to discuss their latest discoveries.

Interdisciplinary research and education united by mathematical approaches

The symposium's seven sessions included two additions this year: a session on mathematics and informatics chaired by Hiroshi Suito, a principal investigator at the AIMR, and another on Tohoku University's new Graduate Program in Materials Science (GP-MS), led by Katsunari Oikawa, a professor at the Graduate School of Engineering. GP-MS officially launches in April 2019, and it joins a growing list of international double-degree programs that includes the Graduate Program in Spintronics (GP-Spin) and the Graduate Program in Data Science (GP-DS).

The addition of this mathematics and informatics session reflects the growing role that mathematics and its applications play in a data-rich world. "At the AIMR, one of our unique strengths is our ability to investigate materials science underpinned by mathematics," said Kotani. "And in today's digitalized society, we are seeing the rise of artificial intelligence, IoT and big data. More and more researchers, not just at the AIMR but around the world, are interested in extending mathematical ideas to these areas. The new session is a good opportunity to showcase what we can do."

Mathematics is a universal language that cuts across traditional disciplines, Kotani said. Commenting on AIMR's allure for the world's top minds, she expressed her hope that more women will be inspired to consider research paths and careers in mathematics and materials sciences.

The three-day symposium, which covered a wide range of fields, was highly successful in promoting multidisciplinary research and international collaboration, thanks to the attendance of collaborators and friends from around the world. It provided a forum for lively discussions about the cutting edge of materials science and spintronics — two fields which the AIMR has been focusing on since its foundation.

A more specialist workshop on glasses had been held as a satellite event a day prior to the symposium. First held in 2012 to promote collaboration between the fields of mathematics and materials science, this workshop has been held every year subsequently. It gave participants more opportunities for in-depth discussions about metallic glasses and other amorphous materials. ■

INTERNATIONAL WORKSHOPS

Published online on 27 July 2019

Promoting interaction between material scientists in Europe and Japan

Two recent meetings in France provided AIMR researchers a unique opportunity to both share their latest results and strengthen ties with European scientists

Two major events in the materials science calendar are the Spring and Fall Meetings of the European Materials Research Society (E-MRS). With a view to enhancing awareness of the Advanced Institute for Materials Research (AIMR) beyond Japan, members from the institute participated in this year's E-MRS Spring Meeting, which was held on 27–31 May 2019. It was organized in conjunction with the International Conference on Advanced Materials (ICAM) of the International Union of Materials Research Societies (IUMRS). As a result of AIMR's long relationship with E-MRS and strong participation in previous meetings, former AIMR director, Motoko Kotani, was one of the five conference chairpersons at this year's spring meeting.

Like in 2014, 2016 and 2018, AIMR joined forces with representatives from the three other materials-related World Premier International Research Center Initiative (WPI) centers, namely the International Center for Materials Nanoarchitectonics (MANA), the Institute for Integrated Cell-Material Sciences (iCeMS) and the International Institute for Carbon-Neutral Energy Research (I^{2}CNER), to promote the WPI in Europe and beyond during this major international conference. A few days after the E-MRS Spring Meeting, the representatives of the four centers jointly participated in NanoMat, a workshop designed to strengthen partnerships between nanomaterials researchers in France and Japan.

Staff at the World Premier International Research Center Initiative (WPI) exhibition booth at the 2019 E-MRS Spring Meeting interacting with visitors.

Combining forces to promote materials science in Europe

As in past years, the four WPI centers ran an exhibition booth at the 2019 E-MRS Spring Meeting to introduce the activities of WPI and the four centers. The booth, which ran for three days (28–30 May), displayed posters and brochures about the WPI project and the four WPI centers. In addition, visitors had the

Left: Hiroshi Yabu discusses using metafluids to strongly enhance molecular sensing at the 2019 E-MRS Spring Meeting. Right: Teng Ma (wearing a white shirt) at the 2019 E-MRS Spring Meeting explaining his poster on improving the stability and performance of perovskite photovoltaics.

chance to win various prizes in a lottery. Outreach staff from the four WPI centers answered questions and described the centers' unique research environments and significant achievements. The booth attracted researchers from a diverse range of fields and countries, including both senior scientists, many of whom had collaborated with Japanese researchers or had stayed in Japan, and young researchers, many of whom were interested in exploring opportunities for advancing their careers at institutions in Japan.

In the scientific sessions, AIMR researchers gave two oral and four poster presentations. Hiroshi Yabu talked about a new class of materials known as metafluids that respond to magnetic fields and that can be used to strongly enhance the sensing of molecules by an analytic technique known as Raman spectroscopy, and Akichika Kumatani discussed analyzing graphite and graphene using a scanning electrochemical cell microscope. In the poster session, Teng Ma introduced his poster on optimizing the lateral structure of materials known as perovskites to realize stable and highly efficient solar cells. His proposal for simultaneously improving the stability and performance of perovskite photovoltaics won the best poster award.

The state of the art in sensors

Immediately after the main E-MRS Spring Meeting, a joint France–Japan workshop on molecular technology for advanced sensors was held as a satellite event. After introductions by Anne Charrier of the Center for Interdisciplinary Nanoscience of Marseille and Yutaka Wakayama, deputy director of MANA, ten invited speakers presented their latest results on a wide range of sensor technologies, including sensors for detecting molecules, gas, light and biomaterials, sensors that use organic field-effect transistors, sensors based on polymers and organic compounds, and sensors that employ electrical, electrochemical and optical transduction. From AIMR, Kumatani talked about nanoscale electrochemical imaging of electrode materials using a scanning electrochemical cell microscope. He proposed a new approach for designing two-dimensional materials, such as graphene, that is based on mathematical output, and he confirmed their high electrochemical performance experimentally by microscopic imaging. His presentation generated a lot of interest, as evidenced by the ensuing discussions. The long relationship between France and Japan in materials science seems set to continue to promote the development of cutting-edge sensor technologies.

Exploring nanomaterials together

After the E-MRS Spring Meeting, the NanoMat 2019 Workshop was held on 3–5 June 2019 at the Jussieu campus of Sorbonne University in Paris. It has been held alternately in France and Japan. This

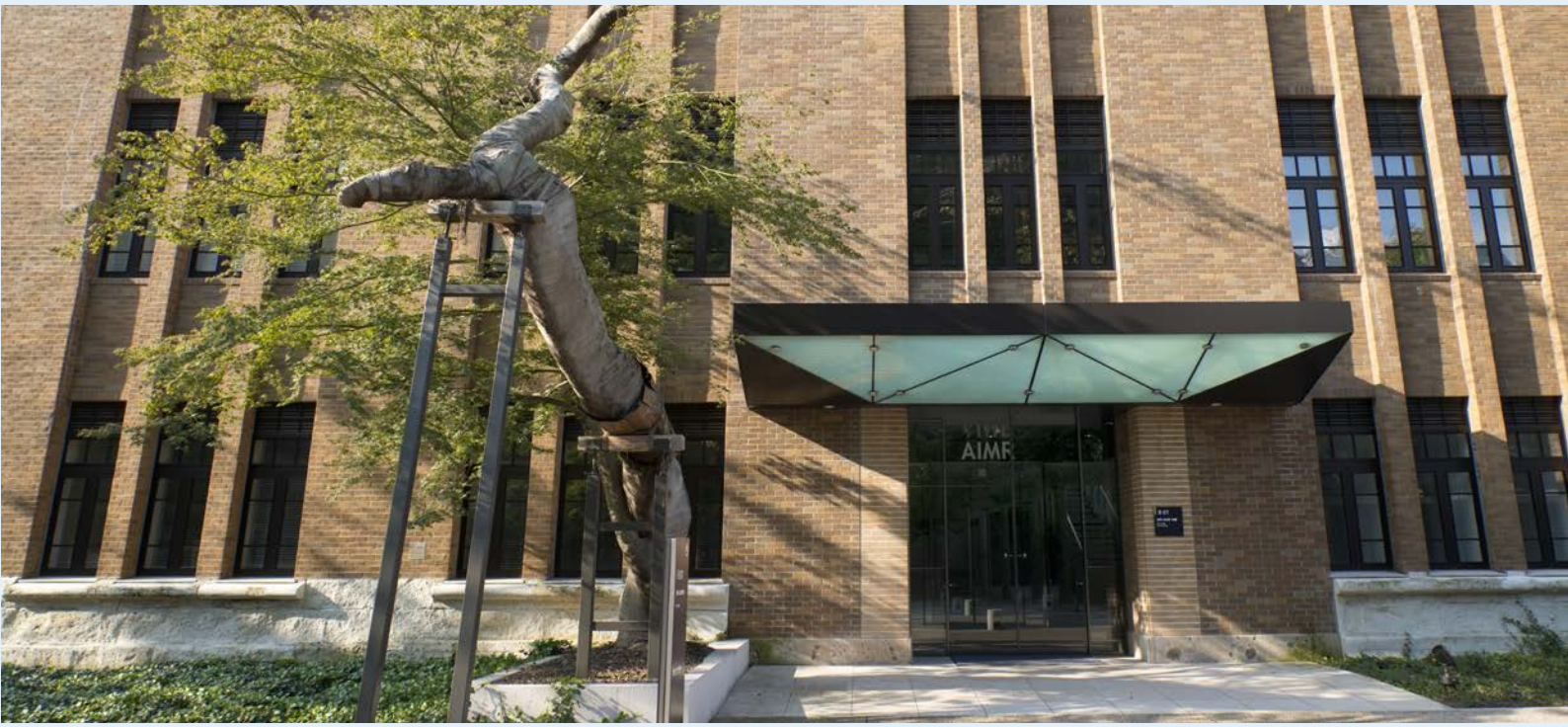
Akichika Kumatani discussing the nanoscale electrochemical imaging at NanoMat 2019.

year it combined the 13th Japan–France Workshop on Nanomaterials and the fourth WPI Workshop on Materials Science. This meeting was co-organized by the French CNRS National Competency Cluster in Nanoscience (C'Nano) and MANA, iCeMS, I²CNER and AIMR.

The workshop started with welcome speeches by Corinne Chaneac, director of C'Nano and the main organizer of this year's workshop, and Stéphane Régnier, dean of the Faculty of Science and Engineering, Sorbonne University. After that, representatives of the four WPI centers, Tomonobu Nakayama from MANA, Hiroshige Matsumoto from I²CNER, Susumu Ikeda from AIMR and Mitsuru Hashida from iCeMS, introduced their respective centers. French and Japanese researchers then gave scientific oral presentations. In the evening, Ma, Ikeda and Hiroya Abe from AIMR presented posters, which all resulted in fruitful discussions with French scientists. On the second day of NanoMat 2019, Yabu talked about synthesizing nanocomposite materials and Kumatani spoke about nanoscale electrochemical imaging on lithium-ion battery electrodes. The meeting included in a facility tour, one highlight of which was a laboratory containing nearly all of the nuclear magnetic resonance (NMR) systems at the Jussieu campus of Sorbonne University.

During the workshop, it was announced that the next NanoMat workshop will be hosted by AIMR in Sendai. This opportunity promises to further strengthen the good relationship in materials science between France and Japan.

These two latest events in France have further raised awareness of AIMR in France and Europe. By participating in future scientific exchange events, including the next NanoMat workshop, AIMR intends to forge even stronger cooperative ties with researchers overseas. ■



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AIM*Research* is published by the Advanced Institute for Materials Research (AIMR) at Tohoku University in collaboration with the Partnership and Custom Media unit of Nature Research, a division of Nature Japan KK.

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ISSN 1884-491X

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