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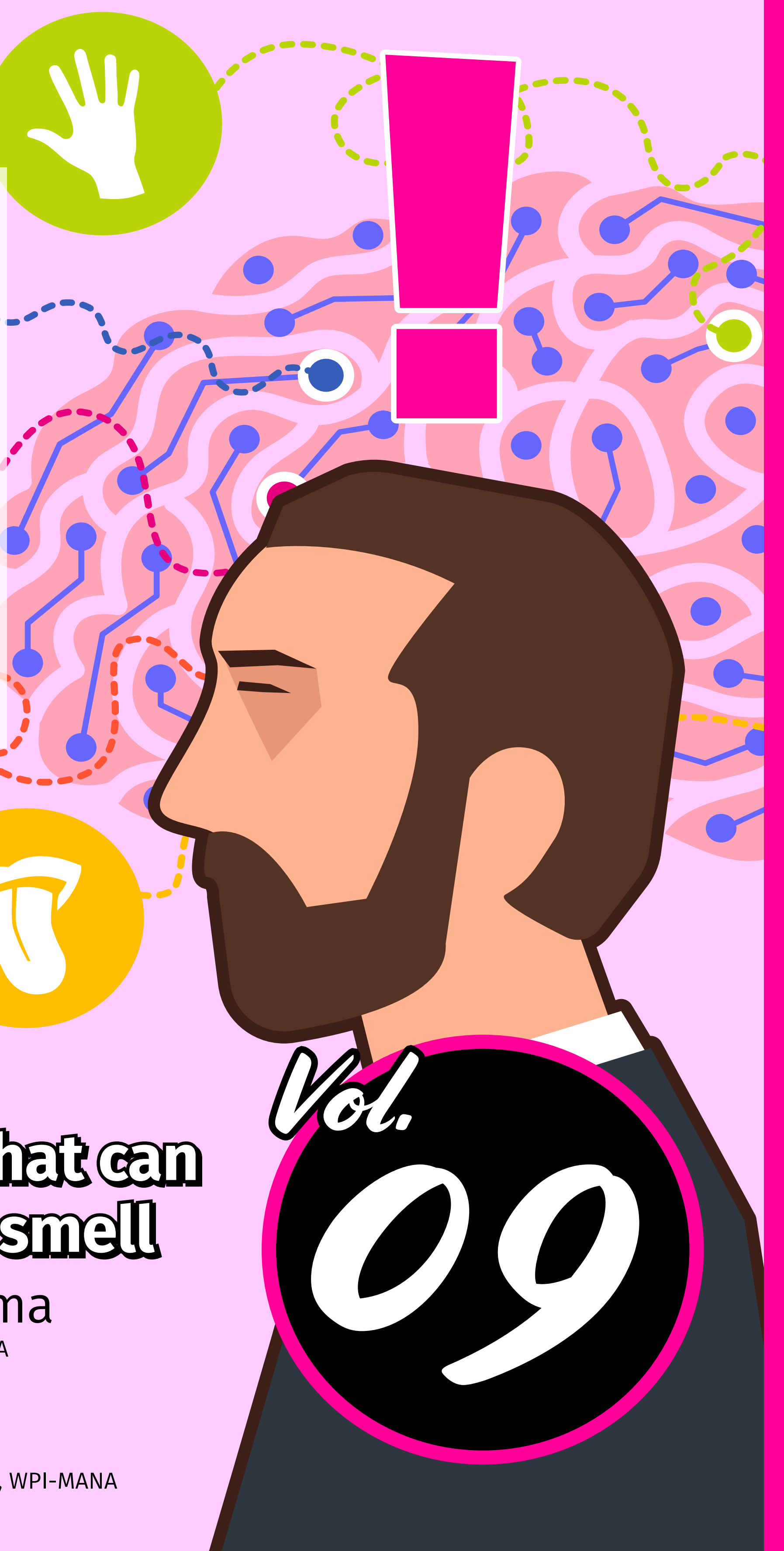

RESEARCH HIGHLIGHTS

FEATURE

Creating systems that can think, feel -- and smell

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Creating systems that can think, feel -- and smell

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MANA researchers are pursuing innovative technologies that mimic the functions of the human brain

Thinking and perception -- the hallmarks of an artificially intelligent system -- are the focus of intense research at MANA, and it is producing exciting results, as well as a host of promising applications.

Two MANA researchers, Tomonobu Nakayama and Genki Yoshikawa, are engaged in work that uses nanotechnology to achieve performance that approaches that of our own biological systems. Dr. Nakayama is developing a nanoarchitectonics network that exhibits emergent cognition -- an artificial brain -- and Dr. Yoshikawa is developing a nano-perceptive olfactory system -- an artificial nose.

Thinking and sensing

Nakayama and his team are using the tools of nanotechnology to create synthetic neural networks that can “think” and “learn,” which could result in novel memory devices.

“Nanotechnology is quite important in integrating nano-functionality into a system,” Nakayama noted. ”And in this case, the sensing and cognitive parts do not rely on software. Probably the type or speed of mechanical motion also imparts cognitive information.”

Brain-like behavior cannot be achieved only by making everything accurate and precise -- there is more to cognition and learning than merely flipping switches on and off. “So we need to think about the relationship between the fluctuation or speed of the action and how to include a variety of uncontrolled natural factors,” Nakayama said.

The team formed their “neuromorphic network” by integrating numerous silver nanowires covered with a polymer insulating layer about 1 nm in thickness. Each junction between two nanowires forms a variable resistive element -- a synaptic element -- which behaves like a neuronal synapse. The resulting structure is like a kitchen scrub made of entangled wire, containing many contacts between the wires.

When it's electrically stimulated, a huge number of junctions interact with each other to achieve the best routing through the network. The electrical signals can exploit multiple transport pathways across the network and spontaneously adapt to changing transmission routes. This process leads to emergent brain-like behavior resembling cognitive functions such as learning, memorization, forgetting, becoming alert and returning to calm.

“In our case, we are not really controlling the kind of contact -- it forms naturally,” Nakayama noted. As a result of that natural formation, the properties of each junction are similar but not exactly the same. They have what is known as “memristive,” or synaptic properties.

“We want to incorporate this sort of memristive device into computer architecture and realize a new form of ‘neuromorphic’ computing,” he said.

The brain is often compared with a computer, but in terms of cognition and recognition, the actual performance of the brain is not really computer-like, Nakayama noted. In conventional computers, everything works according to design. The user inputs a command, and all the transistors and other components do what they’re supposed to. Once the best routing is established, it is registered as a pathway, and does not change.

Nakayama’s network system takes a different approach. “It tries to memorize a better route from one point to another through the network, but we do not control any of the junctions,” he said. “We just give it input, and the network automatically optimizes the routing.”

The routing continues to fluctuate in response to stimuli, and sometimes switches to alternative pathways. “So ‘optimized’ pathways do not always stay ‘optimal.’ They can change in reaction to external stresses,” he said. “Because of this, we don't say this network provides artificial intelligence,” he continued. “We say it's a kind of specific intelligence. It's not, strictly speaking, artificial.”

The team has already made a memory device and computer simulations to show that such a network can be used for character recognition. That kind of task can be done with AI, using computers, but “the difference in this case is that we don't need a computer program, and all the control is done naturally,” Nakayama said.

Detecting and perceiving

Networks that alter and reconsider their decisions need stimuli from the world around them to provide meaningful input.

For example, there's more to a sense of smell than just detecting chemicals in the air around us. We are constantly bombarded by olfactory data, as we detect aromas and compare them to our memories of similar smells to identify them based on past experience. Smell is as much intuition as it is chemical detection.

Yoshikawa is developing an olfactory sensor, a sort of electronic nose, which can identify odors based on both hard data and learning and memory. His sensor combines molecule detection and recognition to make a kind of cognitive sensor.

"A conventional gas sensor gives a one-dimensional signal -- just one number, for example the percentage of oxygen or CO_2," he said. "An olfactory sensor, on the other hand, gives you information about what that smell is. It can measure complicated mixtures of various gases, and once it learns a smell, it remembers how they reacted together."

This is similar to how a biological nose works. "The first time we smell coffee, for example, we remember that sensation and link it to coffee. The next time we smell it, we remember the sensation and identify it as coffee."

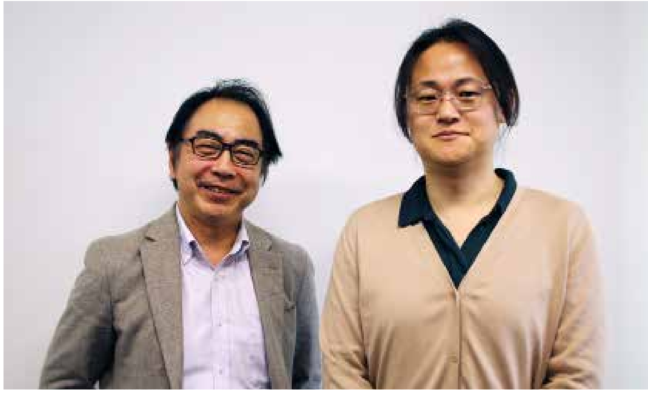
Yoshikawa's device is based on a Membrane-type Surface stress Sensor (MSS), a very sensitive and compact nanomechanical sensor, developed at MANA, capable of detecting a wide range of substances, including gaseous molecules and biomolecules such as DNA and proteins.

When the gas molecules come into contact with the MSS, it experiences mechanical deformation or stress in the nanometer range. The sensor can identify the absorbed molecules by analyzing the degree of deformation based on changes in electrical resistance.

"It is difficult to observe that tiny mechanical deformation, but the sensor can detect it and transduce it into an easy-to-read electrical signal," Yoshikawa said. The results are then analyzed and identified with the help of AI and a huge, and growing, library of olfactory data.

"We perceive smells with intuition as much as with hard data when we are detecting or identifying smells. There is still no rational or logical way of thinking when we smell," he said.

Wide applications



Because of its ability to detect such a wide range of substances, the potential applications of such a device could be widespread. Practical olfactory sensors could make a massive difference in a wide variety of fields, including agriculture, environmental sensing, food management, medicine and criminal investigation.

One dream is breath diagnostics -- using an olfactory device to test for cancer and other diseases by analyzing a patient's exhaled breath. Preliminary results have been positive in differentiating the breath of cancer patients and healthy persons.

The olfactory device could yield basic scientific breakthroughs as well. "One of our goals is to illustrate the mechanism of the nose," he said. "The human nose is super-sensitive -- it can detect parts per trillion. It has about 400 different types of receptors, so the number of odors we can differentiate is almost infinite."

"And still, nobody knows the exact mechanism of how our nose can detect such small concentrations."

New ways of thinking

Because they mimic the workings and natural efficiency of biological cognition, and the inner workings of the brain, future devices based on these MANA researchers' technologies could demonstrate flexibility, speed and energy efficiency similar to the brain's own processing.

These systems can handle tasks in ways that are closer to how human beings operate. Instead of merely enhancing or reprogramming existing computers, they point the way toward an entirely new way of computing -- and major advances in machine learning and AI. ■

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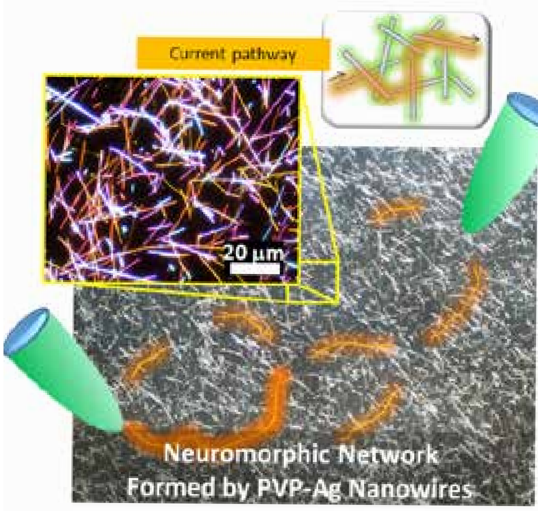
[Vol. 56]

How Do Neuromorphic Nanowire Networks Find Routes to Convey Signals?

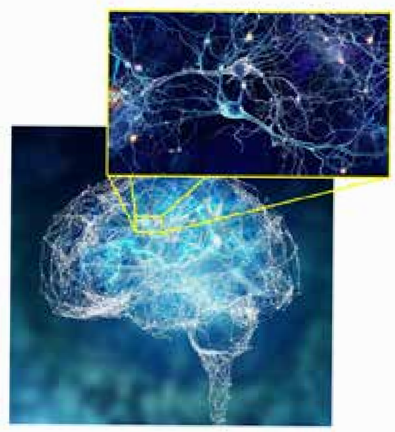
Researchers at MANA have investigated the dynamical behavior of neuromorphic systems made of memristive nano-switches connected together forming complex networks. They have shown experimentally the interplay between network topology and memristor dynamics giving rise to self-organized states.

In self-assembled networks of polymer-coated silver nanowires, the junction between two connected nanowires acts as a memristive switch. Upon application of current-voltage cycles it is seen that the network as a whole also behaves as a memristor, showing critical activation. However, when transient signals are applied to the network, random events produced by the breakage of individual junctions could affect the conduction properties of the whole network.

Thousands of memristive junctions interact when electrical current is passing through, dynamically routing current through the network as switching events occur between individual nanowires. This complex dynamical landscape has been sorted out by devising an original measurement scheme in which both the static and dynamic properties of the network are systematically distinguished. It has been shown that the critical activation that is characterized by a sudden increase in conductance through networks is accompanied by a change in the power-law collective dynamics. The MANA researchers discovered that an activated network finds a route to convey current in a self-organized manner, but sudden bursts of reorganization events occur whenever individual junctions fail, and the network finds other pathways, thus self-repairing.



Micrograph of the neuromorphic network fabricated by this research team. The network contains of numerous junctions between nanowires, which operate as synaptic elements.



A Human brain and one of its neuronal networks.

This emergent and collective behavior provides a promising venue not only to understand better the collective dynamics of other complex systems, i.e., the brains, but also to explore new strategies for hardware integration of these networks as unconventional computing devices with the capability to perform machine learning tasks.

This research was carried out by Tomonobu Nakayama (Deputy Director, MANA Principal Investigator (PI), MANA, NIMS) and his team. ■

Reference

"Emergent dynamics of neuromorphic nanowire networks", Adrian Diaz-Alvarez, Rintaro Higuchi, Yoshitaka Shingaya, Adam Z. Stieg, James K. Gimzewski, Zdenka Kuncic, and Tomonobu Nakayama, *et al.*; Scientific Reports [October 17, 2019]
DOI: 10.1038/s41598-019-51330-6

[Vol. 57]

'Liquid Electret' Could Offer New Power Source for Wearable Electronics

Researchers at MANA have created a material that could power a new generation of wearable electronic mobile devices.

The finding is another step toward realizing what could be numerous potential applications for flexible mechanoelectrical devices in self-powered wearable electronics, including healthcare sensors such as pacemakers, surgery tools, muscle-driven energy harvesters, communications devices and smart textiles.

The new "liquid electret" material has the mechanoelectrical and electroacoustic functions, as well as the flexibility and stretchability, that would be crucial in a reliable and long-lasting power source for such devices.

The newly developed liquid electret material (right) and the bendable and stretchable vibration-powered device (bottom left)

Electrets are key components for powering mechanoelectrical devices as they behave like a battery or as an electrical counterpart of a permanent magnet.

Electrets used in such devices are generally solid films composed of insulating polymeric materials. However, a liquid electret material would be a better solution -- it would be flexible and stretchable, and greatly enhance the usability of the devices they power. In addition, liquids offer fluidity with fast diffusion of molecules, easy processing, lack of defects and high deformability -- all requirements for flexible/stretchable device technologies.

The MANA researchers developed a new method of producing electrets, using a shielded π-unit of liquid porphyrins with trapped charge to create their liquid electret, which they fabricated to demonstrate its mechanoelectrical and electroacoustic functions. They shielded the π-core with hydrophobic and insulating bulky-alkyl side chains, enabling the liquid porphyrins to store an electric charge.

This molecular design of the unconventional liquid electret presents a new direction toward mechanoelectrical and electroacoustic applications for advanced wearable/stretchable electronics.

This research was carried out by Takashi Nakanishi (Group Leader of Frontier Molecules Group, MANA, NIMS) and his collaborators. ■

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"Soft chromophore featured liquid porphyrins and their utilization toward liquid electret applications", Avijit Ghosh, Manabu Yoshida, Kouji Suemori, Hiroaki Isago, Nagao Kobayashi, Yasuhisa Mizutani, Kazuhiko Nagura, Shinsuke Ishihara and Takashi Nakanishi, *et al.*; Nature Communications [September 30, 2019]
DOI: 10.1038/s41467-019-12249-8

[Vol. 58]

New Insights into Structure of Layered Hydrogen Borides

A team of MANA researchers has determined the structure of a layered hydrogen boride synthesized via a soft chemical route. The team found that the structure consists of B-H-B bridging bonds and B-H terminal bonds, and the local structure induces macroscopic amorphous nature by "geometrical frustration." Since the layered hydrogen boride is electrically conductive, the finding points the way toward new applications.

The team determined atomic arrangements in the layered hydrogen boride by using pair-distribution functions (that is, the probability of finding two atoms separated by a certain distance in the material). It found that the material mostly consisted of a corrugated B network decorated with three-center, two-electron B-H-B bridging bonds, as well as ordinary two-center, two-electron B-H terminal bonds. It was locally ordered but amorphous by diffractometry.

The team accounted for this discrepancy by positing geometrical frustration, caused by the positions of terminal B-H bonds located on one of two equivalent B atoms in the B-H-B bridging bonds. This geometrical frustration accounts for the amorphous state of the layered HB and the team dubbed this structure "frustrated hydrogen boride" (f-HB).

Local B-H chemical bonds in f-HB appear to govern its macroscopic structure as well as its conductivity upon adsorption of molecules. The material is electrically conductive rather than ion-conductive, and its B-H-B bonds are cleaved by the adsorption of molecules.

Because f-HB is an electrically conductive solid-state material with local functional groups that respond to chemical adsorption, these findings could open up unique functionalities of HB materials, such as HB nanosheets as potential sensing materials and catalysts.

This research was carried out by Satoshi Tominaka (Senior Researcher, Soft Chemistry Group, MANA, NIMS) and his collaborators. ■

Chemical synthesis of hydrogen boride nanosheets. This molecular-level-thick sheet material has unique hydrogen arrangements and is electrically conductive. Its electrical conductivity is sensitive to the influence of molecular adsorption on its surfaces.

Reference

"Geometrical Frustration of B-H bonds in Layered Hydrogen Borides Accessible by Soft Chemistry", Satoshi Tominaka, Kohsaku Kawakami, Takuya Masuda, *et al.*; Chem [February 13, 2020]
DOI: 10.1016/j.chempr.2019.11.006