Combining Nanomechanics and Ultrahigh-speed Magnophononic Technology Makes It Possible to Use Phonon Signals as Information Carrier Other Than Electrical and Optical Signals

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Abstract

The Innovative Optical and Wireless Network (IOWN) will transform the information carriers not only in the transmission lines but also in the internal circuits of computers from electrical signals to optical signals. The key to achieving this is an optical transistor, which can be fabricated using photonic crystals that can confine and control the light within devices. A completely different approach to device technology, i.e., using acoustic waves (elastic waves) in the gigahertz frequency range, has also been extensively studied. As a fundamental research topic, nanomechanics is being researched to enable low-power information processing and ultra-sensitive signal detection by controlling the propagation of acoustic waves in the nanoscale domain. One of the techniques studied in nanomechanics is the use of a nanoscale artificial structure called phononic crystal, which confines and controls the acoustic waves in a device. We interviewed Hiroshi Yamaguchi, an NTT Fellow at NTT Basic Research Laboratories, who is engaged in research on nanomechanics, about the current status and future prospects of his research, changes in the circumstances surrounding the basic research, and his thoughts on how researchers should conduct their research with those changes in mind.

Keywords: nanomechanics, nonlinear nanomechanical device, magnophononic technology

Fabricate new functional devices by using nanomechanics and ultrahigh-speed magnophononic technology

—Would you tell us about the research you are currently working on?

I have been researching nanomechanics for more than 10 years. Optical devices and semiconductor devices exploit the physical phenomena of light and electrons, whereas nanomechanics uses the mechanical properties of acoustic vibrations in microstructures. An acoustic vibration is something like the sound transmitted to the end of the desk when you tap the other edge of a desk or the vibration continuing at a fixed pitch when you tap a tuning fork. As electric devices, quartz crystals use the acoustic vibrations as watches and computer clocks to keep time. Embedding a slice (thin film) of quartz crystal into a circuit causes the crystal to vibrate at a very precise frequency. This phenomenon is applied to provide highly accurate frequency signals for many numbers of watches, computers, and other types of electronic devices.

Microelectromechanical systems (MEMS) have been extensively studied to use such elastic acoustic vibrations in electronic devices, and nanomechanics can be called the next-generation technology of MEMS. Using the nonlinearity of the elastic properties or combining it with quantum-device technology enables the fabrication of devices with functions not possible with MEMS (see **Table 1**).

"Nonlinearity," which may be an unfamiliar term, means that the output of the device is not proportional to the input. In fact, semiconductor devices, such as diodes and transistors, have demonstrated a variety of functions through their nonlinearities. These functions cannot be provided by devices with linear characteristics such as inductors, capacitors, and resistors. For example, the current flows through a resistor in proportion to the applied voltage. With a diode, however, the current and applied voltage are not proportional. For transistors, this nonlinear characteristic changes in accordance with the voltage or current applied to the electrode. For acoustic vibrations, this nonlinear characteristic corresponds to the fact that the magnitude of vibration is not proportional to the force applied to the material, and the effect of such nonlinearity becomes more pronounced with miniaturization of the device. By exploiting such nonlinear characteristics, my research colleagues and I aim to create nonlinear nanomechanical devices with innovative functions similar to those of diodes and transistors.

Integration of nanomechanics with quantum-device technology is expected to enable the fabrication of new functional devices. When a nonlinear nanomechanical device is combined with quantum dots, for example, it is possible to detect extremely fine vibrations equivalent to the diameter of an atomic nucleus. By incorporating semiconductor lasers and other devices, a nonlinear nanomechanical device can control optical signals. These applications require ultrahigh-speed operation at frequencies above 1 gigahertz (GHz).

We have been focusing on phonon hybrid devices, which combine quantum devices and nanomechanics. As the smallest units of acoustic vibration, phonons are attracting attention through their integration with quantum technology. From 2015 to 2019, I was the principal investigator of a research project called "Phonon hybrid quantum science" in a research area of the "Science of hybrid quantum systems" in the Grant-in-Aid for Scientific Research (KAKENHI) and explored quantum technology using phonons. In this project, co-investigators and I succeeded in incorporating a new function into nanomechanics by combining phonon devices with semiconductor quantum structures. We are currently investigating new phonon hybrid devices as advanced technologies that integrate not only semiconductors but also other material systems such as magnetic materials, rare-earth elements, and solutions.

For example, we have been studying the phononic crystal, an ultra-fine artificial structure that confines acoustic vibration. This is the acoustic analogue of phononic crystals, which confines light waves in an artificial structure. By combining the phononic crystal with ferromagnetic materials, we have recently succeeded in demonstrating a phenomenon called ferromagnetic resonance in a region 10,000 times smaller than that possible with conventional methods. Ferromagnetic resonance is a phenomenon by which magnetic materials are sensitive to alternating current signals of a fixed frequency and expected to be applied to ultra-sensitive magnetic sensors and information processing using magnetic materials. These applications are examples of new hybrid devices combining nanomechanics and magnetism. We also fabricated an acoustic resonator that operates at ultrahigh-frequency ranges (30 GHz or higher) using a nitride-semiconductor single-crystal thin film (**Fig. 1**) [1]. We believe that this achievement will enable ultrafast operation by combining various

Table 1. Comparison of devices and functions concerning electronics and micro/nanomechanics.

	Linear device	Nonlinear device		Quantum device
		2-terminal device	3-terminal device	
Electronics	Inductor Capacitor Resistor	Diode	Transistor	Quantum bit Quantum memory
	Tuner Filter	Demodulator Rectifier	Amplifier/switch Memory/logic	Quantum computing Quantum sensing
Micro/nanomechanics	Resonator	Future research targets		
	High-frequency filter Sensor/gyro Microphone			

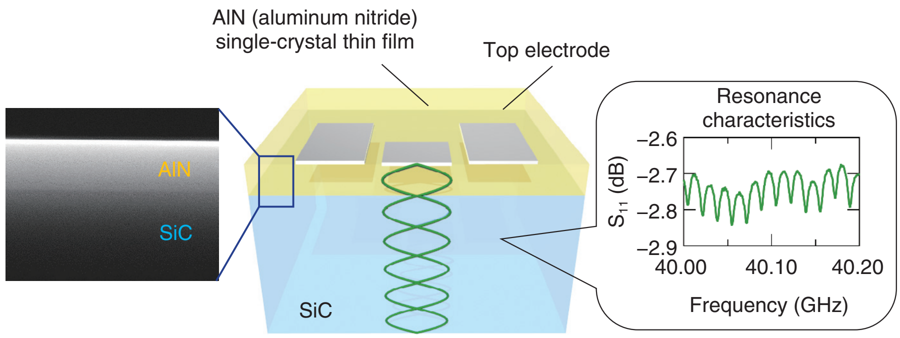

Fig. 1. Acoustic resonator (fabricated using a nitride-semiconductor single-crystal thin film) and its resonance characteristics [1].

materials and quantum structures as hybrid devices. We also believe that this will potentially impact the development of mobile technologies such as high-frequency microwave filters.

—I heard that you have launched a new KAKENHI project.

In April 2023, we started a joint research project with the University of Tokyo on the theme of “Ultrahigh-speed magnophononic resonator devices,” which is a KAKENHI project administered by Japan Society for the Promotion of Science. Memory in computers stores states of 0 and 1 in accordance with whether electrons are accumulated in a specific area of a semiconductor; in contrast, magnetoresistive random-access memory (MRAM) stores information in an electronic device by assigning the N (north) and S (south) poles of a magnetic material (instead of a semiconductor) as 0 and 1. Ultrahigh-speed magnophononic technology combines technology that uses magnetic materials, such as MRAM, and technology that handles acoustic vibrations (**Fig. 2**) [2].

Ferromagnetic materials enable devices to operate at extremely high frequencies, as high as 100 GHz, and have non-volatility, which allows them to maintain such a state. By combining ferromagnetic materials with phononic devices, ultrafast hybrid devices that harness the non-volatility of ferromagnetic materials can be fabricated. For example, programmable operation for high-frequency signal processing may be possible by using such hybrid devices in sensors and timing devices used in mobile terminals. For conventional electronic circuits, as frequency increases, electrical signals leak out as electromagnetic waves, which cause strong interference between circuits. If this interference can be avoided using magnophononic technology, phonon signals could be used as a new information carrier to replace electrical signals. If magnetic sensing with sensitivity comparable to that of superconducting quantum interference devices, which require cryogenic temperatures, can

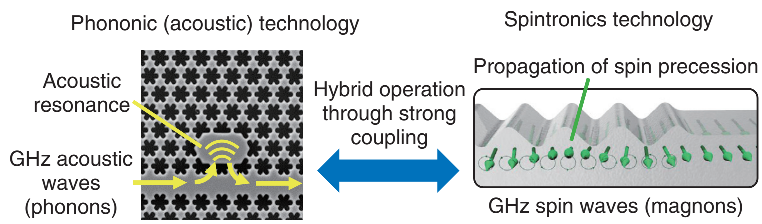

Fig. 2. Conceptual diagram of ultrahigh-speed magnophononic technology [2].

be achieved at room temperature, it could be used in medical devices such as magnetoencephalographs. Application of magnophononic devices as micron-sized ultra-small high-frequency antennas has also been proposed, and such devices could significantly change the performance of mobile terminals. While keeping these applications in mind, we also want to pursue fundamental research on physical properties, such as the interaction between magnetism and vibration, which still has many aspects that have not been elucidated.

Breaking away from an inward-looking mindset and building research collaboration

—The circumstances surrounding Japan's basic research are changing drastically, right?

I sense three major changes. First, connections with overseas researchers have become weaker. International conferences and meetings have shifted to online due to the COVID-19 pandemic, but the effectiveness of face-to-face contact and discussion at in-person conferences cannot be replicated online. I have given three presentations at international conferences outside Japan since the beginning of 2023, and even now that the classification of COVID-19 has been downgraded to the same level as seasonal influenza in Japan, I feel that the number of Japanese researchers participating in international conferences and other events is smaller than that before the pandemic. The number of young researchers who travel abroad is particularly low. I suspect that the reason for that is the remaining high level of vigilance against COVID-19 infection and increased airfares due to the rising cost of fuel and the longer flights due to the inability to transit over Siberia. The more advanced research becomes, the more difficult it becomes for a single group to conduct it, so research exchanges with researchers inside and outside the country have become essential. In such cases, personal connections with overseas researchers can be of great help. Internationalization of young human resources is an important issue facing various research fields, and sending young researchers abroad to participate in joint research is crucial in basic research. Japan is said to be inward-looking these days, I think we should increase our contacts with overseas researchers and promote internationalization and diversification of our research.

The second major change is the remarkable advancement of other Asian countries. China, especially, has a large population and an order-of-magnitude-more funding for research. A simple proportional calculation based on these factors would indicate that the numbers of talented researchers and world-class laboratories are overwhelmingly large. This is especially true in new research fields. Although I believe Japan and NTT are still in a position to lead the world in optical and semiconductor technologies, we cannot let our guard down. I think that we will need to further improve collaborative research and research processes, including the selection of fields and themes, and we are currently investigating ways to make those improvements.

The third major change is the emergence of generative artificial intelligence (AI). Many tasks, such as writing abstracts and introductions of papers and automatically creating programs for experimental apparatus, can be made more efficient by using generative AI. This capability can cause changes in the research processes that I mentioned above. While researchers in some countries are actively promoting the use of generative AI, issues concerning copyright, credibility of research results, and the literacy of users are being discussed in various fields. How to apply generative AI to our research is a major challenge.

Recommendation for "detour research"

—Please tell us what you keep in mind as a researcher.

In my previous interview, I emphasized three points: (i) setting goals that are different from others, (ii) while focusing on your own strengths, pivoting into other fields, and (iii) extending the antenna high and wide to obtain new and useful information. I'll discuss the following three additional points as well as further explain the above three points based on my research style.

In a new field of basic research, obtaining results at an early stage greatly influences subsequent attention, so many researchers focus on research themes that have a clear logical structure and precise idea of what needs to be done. However, such research themes are easily noticed by other researchers, so competition between researchers is fierce. Therefore, I recommended setting goals that are different from others in the previous interview. If a theme of interest comes up during the course of research, I think it is important to take a detour to that theme while leaving the initial goal as it is. If the theme is likely to have an even greater impact on your field of research, you should boldly change your goal in that direction. If taking a detour does not seem to work, you just return to the initial goal. While it is important to stick to your initial goal, it is also important to be flexible in changing the theme with a freer mindset.

The practice of give and take is often taught when researchers are collaborating, whether it is joint research, activities concerning academic societies, or sharing research within a team. Many people tend to think of taking exactly 50%, and some take as much as possible. However, your partner will be thinking in the same way, so a struggle will occur between you and them. Therefore, if you think about giving and taking at a ratio of 7:3, you will make your partner think that it is highly beneficial to work with you, and the collaboration will go well. This is a lesson from my former senior. Even if you think the give-and-take ratio is 7:3, it is often 6:4 when you actually try it. It could also be reversed to a ratio of 4:6. The important point is how to create the conditions for a positive commitment from both partners.

I believe that there are no higher or lower ranks in the thoughts and ideas of each researcher, especially regarding basic research; that is, all researchers should be equal regardless of whether they are in managerial or non-managerial positions. The above 7:3 give-and-take practice should also be applied between managers and non-managers. Even if you are a manager, it is important to respect the other person's idea and make decisions on the basis of correct knowledge and logic. Therefore, a frank exchange of information will occur and good ideas will emerge. This attitude is also in line with the motto of Shoji Yoshida, the first director of NTT Basic Research Laboratories, "All members of NTT Basic Research Laboratories share the common principle of acting voluntarily and proactively with strong will and humility without falling into the trap of self-righteousness." With that in mind, Director Yoshida chose the word "will" as the attitude required of researchers at the laboratories. I do not think the importance of that attitude has changed, even after nearly 40 years.

Streamlining the research process and valuing what you have

—What is your message to younger researchers?

When you start your first step as corporate researchers, many of you will be involved in research in different fields from what you specialized in when you were students. When I was a student, I researched theoretical particle physics; however, when I joined NTT, I was involved in the completely different field of experimental research on semiconductors. At that time, I was almost an amateur researcher on semiconductors, and I had a sinking feeling that the knowledge I had worked so hard to accumulate as a student would be completely meaningless. However, over the years, I have found that I can make surprisingly good use of my knowledge from my student days in my research on nanomechanics. It may be that my past expertise served as a potential trigger for me to start researching nanomechanics. This outcome is true not only for scientific expertise but also for all past experiences such as club activities and volunteer work. I think that people who have made great efforts in the past will be more inclined to try to make use of that experience, and that is why they made the effort to do so. However, when they enter a new environment, they often find that their experience does not immediately translate well to the new environment. If this is the case, you should not immediately reject that environment; instead, it is important to plan your lives with the attitude that opportunities in which you can make use of the experience will surely arise.

The environment in which research is conducted has changed dramatically since the words "work-style reform" and "work-life balance" became commonplace. In addition, the "universalization of information," allowing anyone to retrieve a variety of information with a single keyboard operation by asking a search engine or AI, is progressing. In other words, we are entering an era in which anyone can easily do what was previously only possible for experienced researchers. To conduct highly original research in this environment, it has become even more important to work efficiently by focusing on what you are best at. It is therefore necessary for researchers to re-evaluate where they are going to compete and for managers and non-managers to respect the individuality of each researcher, rather than imposing a uniform methodology onto them.

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■ Interviewee profile

Hiroshi Yamaguchi received a B.S. and M.S. in physics and Ph.D. in engineering from Osaka University in 1984, 1986, and 1993. He joined NTT Basic Research Laboratories in 1986. His current interests are in micro/nanomechanical devices using semiconductor heterostructures. He is a fellow of the Institute of Physics and Japan Society of Applied Physics and a member of the American Physical Society, the Physical Society of Japan, and the Institute of Electrical and Electronics Engineers.