Set a Goal Differing from Those of Other People and Achieve It Using a Pivot Strategy

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Overview

As optical communications continue to spread, the results of research on the physical properties of light, electricity, and electrons to achieve high speed and low power consumption of such communications are being put to practical use. New physical phenomena have been discovered and explained by the interaction of the physical properties of mechanical vibration and those of light, electricity, and electrons. We asked Hiroshi Yamaguchi, a senior distinguished researcher at NTT Basic Research Laboratories, who has produced several world-first results in regard to applied technologies in the relatively new research field of nanomechanics, about his research activities and his attitude as a researcher.

Keywords: nanomechanics, MEMS, phononic crystal

Fabricating new micromechanical devices to discover new physical phenomena

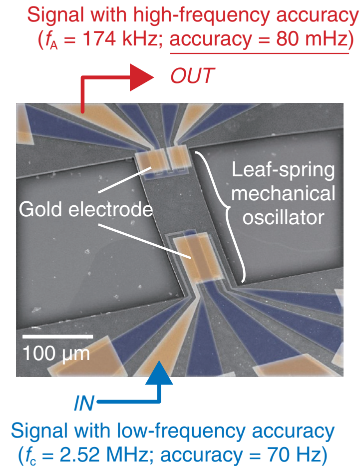
—Please start with the research you are currently conducting.

I and my co-researchers are fabricating micron-scale mechanical devices using semiconductor heterostructures and using its mechanical properties to develop novel devices used in integrated circuits (ICs). More specifically, we fabricate a mechanical device with an ultrafine structure (for example, a device with a leaf-spring structure) by using high-purity semiconductor crystals. We then experimentally use that device to discover and examine new physical phenomena caused by fusing the physical properties of light, electricity, and mechanical vibration, and develop novel devices used in ICs by exploiting those phenomena.

When an electric voltage is applied to an object, mechanical expansion and contraction occurs, which is called the piezoelectric effect. If a semiconductor material is used for fabricating a mechanical device, this effect can be combined with the opto-electrical properties of semiconductors, making it possible to switch between three types of signals: light, electricity, and mechanical vibration. Adding a new degree of freedom, namely, mechanical vibration, to the interaction between light and electricity will reveal new physical phenomena, which will open up applications for ultrasensitive electrical, optical, and molecular sensors and new signal-processing technologies.

Moreover, by fusing these physical phenomena with semiconductor quantum structures such as quantum wells and quantum dots (in which the quantum-mechanical properties of electrons appear), it will be possible to fabricate new hybrid quantum devices.

We are investigating new applied technologies by using microelectromechanical systems (MEMS)*1 and nanoelectromechanical systems (NEMS). MEMS and NEMS are attracting attention from both academic and practical viewpoints as microstructure devices that cause mechanical vibration. We have fabricated functional mechanical devices such as (i) an ultrasonic laser called *sound amplification by stimulated emission of radiation* (SASER), which can output extremely high-precision and high-quality ultrasonic vibrations by applying a principle similar to that of lasers to a mechanical oscillator (**Fig. 1**), (ii) an ultrasensitive sensor that can detect slight changes in weight and charge from minute movements of mechanical elements (**Fig. 2**), and (iii) signal-processing devices (such as memories and processors) that use elastic vibration.



The orange components, namely, the gold electrodes, are used for signal input/output. The blue areas show the conductive semiconductor layers. The leaf-spring mechanical oscillator (in the center) vibrates in the out-of-plane direction. In the experiment, when vibration with low-frequency accuracy was input from the bottom electrode, a signal with extremely high-frequency accuracy (i.e., frequency fluctuation of only 80 mHz) was output from the upper electrode.

Fig. 1. Electron microscope image of SASER.

—I heard that you are making globally important accomplishments. Could you introduce them to us?

Artificial crystals called phononic crystals—to which the concept of photonic crystals*2 is applied to control phonons (namely, media for transmitting sound, vibration, and heat via elastic vibrations of substances)—are attracting attention as a new category of functional materials that can control the sound, vibration, and heat that phonons can propagate. A phononic crystal has an artificial structure in which different elastic bodies are periodically arranged on a micron scale (**Fig. 3**). Since it has been difficult to electrically and externally control the operation of conventional phononic crystals, their application as active devices has been limited. We have successfully demonstrated—the world's first—in electrically controlling the propagation of phonons by using a semiconductor MEMS resonator (which can electrically control mechanical vibrations) as the basic device of a phononic crystal. This achievement was published in the scientific journal *Nature Nanotechnology* in 2014 [1, 2]. In 2018, using a phononic crystal that can manipulate the flow of ultrasonic vibration, we demonstrated the amplification of ultrasonic signals by waveform compression. This achievement was published in the online version of the scientific journal *Nature Communications* [3, 4]. Semiconductor devices that use ultrasonic signals are widely used in mobile terminals and other electronic equipment. If advanced control of those signals is enabled, new and various applied technologies would spread. Furthermore, we have recently been developing more-advanced ultrasonic-vibration control technologies such as the generation of chaos*3 and solitons*4 by exploiting the nonlinearity associated with mechanical resonators. We have also successfully fabricated a phononic-crystal waveguide that operates with high-frequency (gigahertz) vibration due to the miniaturization and high speed of mechanical resonators.

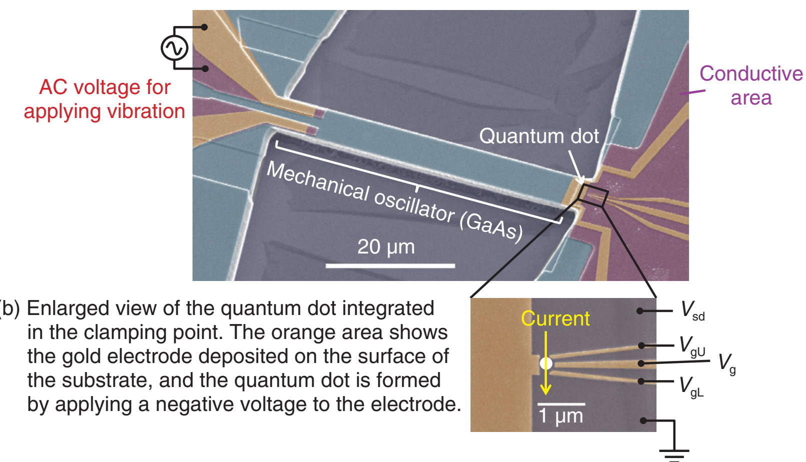
*1 MEMS: A type of miniature machine that has both mechanical and electrical functions. MEMS technology integrates mechanical structures of several millimeters to several microns on a chip by using microfabrication technology used for making semiconductor ICs.

*2 Photonic crystal: A material with a structure consisting of different refractive media that are periodically arranged on the order of the wavelength of light.

*3 Chaos: Common physical phenomena observed in many systems, such as the growth of populations of living species, turbulence of water, electric circuits, and laser light. It is a complex behavior that seems to be random at first glance but has a reproducibility in that it shows the same behavior under the same initial conditions.

*4 Soliton: A solitary wave that maintains its waveform while it propagates or a solitary wave that its waveform repeatedly compresses and expands periodically during propagation. The former is called a fundamental soliton, and the latter is a higher-order soliton.

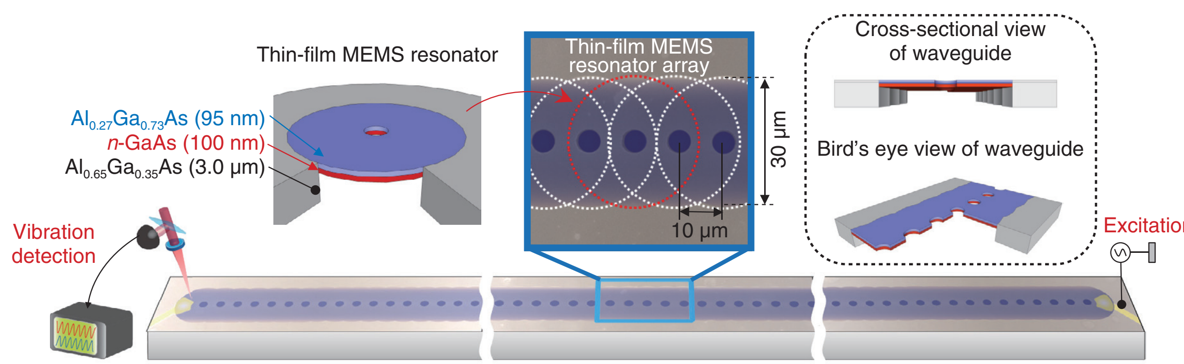
(a) Ultrasensitive vibration sensor using a quantum dot. When the oscillator vibrates up and down, strain is applied to the quantum dot integrated in the clamping point of the oscillator. By detecting this strain as an electric current, it becomes possible to detect vibration with high sensitivity.



(b) Enlarged view of the quantum dot integrated in the clamping point. The orange area shows the gold electrode deposited on the surface of the substrate, and the quantum dot is formed by applying a negative voltage to the electrode.

AC: alternating current
GaAs: gallium arsenide

Fig. 2. Ultrasensitive sensor.



Using compound semiconductors enables electrical excitation and vibration detection.

Fig. 3. Phononic crystal waveguide incorporating one-dimensional array of 100 MEMS resonators with a circular thin-film vibrating section.

New properties that emerge due to nonlinearity, such as the generation of chaos and solitons, have the potential to greatly expand the functionality of mechanical devices. For example, a soliton is known to be generated in an optical fiber and is attracting attention as a special wave the shape of which is not changed by propagation. If such ultrasonic signals (i.e., that special wave) can be generated using mechanical devices, it will be possible to develop semiconductor devices that can process signals with high efficiency. Regarding the application of chaos by using mechanical devices, the possibility of efficient machine learning has recently attracted attention, and a method of controlling that chaos is being actively researched. It is expected that these methods can be widely used in applications requiring low power consumption, miniaturization, and integration, such as mobile communication systems (mobile phones, etc.) and Internet-of-Things technologies.

In the future, we would like to focus on overcoming the low speed, which is the most significant weakness of mechanical devices, and expanding our demonstration experiments using compound semiconductors to other materials with superior properties. Unless you are an expert in the properties of matter and applied physics, it may be difficult to understand the importance of changing materials and the bottlenecks to implementation. Even a slight change in materials will completely change the fabrication method and the effects of mechanical devices. However, it takes some time to produce the best results with different materials. Since we are in charge of basic research, it will take a long time; and we would like to persistently research technologies using new materials over the next three to five years.

Extend the antenna high and wide to obtain and disseminate information

—How do you feel about producing several world firsts in a row?

To announce a world first is to present something that has not been asserted by any one; therefore, it requires a certain amount of preparedness. Such an announcement may be interpreted wrongly, and many counterarguments are expected. Regardless, it is important to make a decision to publish it without hesitation. Of course, it is also necessary to prepare for responding to counterarguments to some extent. In 2013, we presented our research on the creation of phonon lasers that use the diverse dynamics of phonons. MEMS made from compound semiconductors exhibit nonlinearity in their vibration response. We found that this nonlinear phenomenon can be used to induce interactions between different vibration modes, enabling the output of high-quality ultrasonic vibrations.

This principle is similar to that concerning a laser of light, so we called it a "phonon laser" and announced it. However, there were various opinions about whether our achievement could be regarded as a "laser." Announcement of world-first achievements invites controversy, including such counterarguments, so it takes courage to deliberately plunge yourself into that controversy. However, if you are always afraid, you won't be able to announce your results, so you have to make a decision at some point. In fact, this presentation of the phonon laser was subsequently selected by the American Physical Society as one of the eleven best papers of "2013 Highlights of the Year" and introduced as one of the achievements getting the most responses from all disciplines across a wide range of physics. In that sense, I think it was a result that was widely accepted by many researchers at academic societies. The more new results you obtain, the more important it is to have the courage to present your ideas, even if you hear different opinions.

—What has been the most-important point when doing research?

As a researcher, I have always set goals that differ from those of others. Setting the same goals makes it easier to explain the purpose of research; however, differences from other researchers can be found only in regard to the research methodologies, and the choice of research itself is narrowed. In the research fields in which those goals are gaining attention, major research institutes around the world devote a great deal of their funds and compete by mobilizing excellent researchers. Students from prestigious international universities are outstanding in terms of motivation, knowledge, and abilities, and such students are working together and competing with the same goal in mind. It is true that Japanese students are also outstanding, and the students I teach are doing their best, but I have to say that it is difficult to compete with other students in international universities.

In such a situation, our policy is to compete by including the goal setting in the purpose of research. I think that selecting nanomechanics, which almost no one was working on at the time we started research, and targeting signal processing using ultrasonic signals is an example of setting goals that differ from those of other researchers. At first, no one else looked at that topic, but after a while, many related studies citing our paper emerged. It is precisely because we tried to create new goals that we were able to lead in new research fields.

When setting goals, I think it is better not to collect too much information. To be precise, when collecting information, I try to collect information in a manner that is not narrow and deep in one's own field but broad and shallow covering other fields. For example, when working on nanomechanics, I use the perspective of optical technology. Regarding the term "nonlinearity" that came up in the previous question, since research on nonlinearity in optical technology is progressing considerably, I ponder whether nonlinearity can be applied to nanomechanics or whether transistors, which have been studied for a long time in the field of semiconductors, can be applied to nanomechanics. In this manner, it is important to take inspiration from broader fields and use it when setting goals.

It is indeed important to step into a field different from your own. At that time, however, it is necessary to firmly identify your specialty and keep your foot there then take a step into another research field. If the direction of the goal of the research field matches your specialty, you go in that direction, but if the directions do not match, you pivot into another field. By repeating this process, you will gradually lay the groundwork for setting new goals. This approach is similar to *pivoting* in basketball. By using such a *pivot strategy*, you can proceed with research in a new direction while making the most of your specialty.

The role of an academic society is vital in not only collecting information by extending our “antenna” high and wide but also disseminating information (transmitting radio waves). For researchers in my age group, the number of jobs outside my research group, such as external committees and international conferences, increases, and during my busiest time, I was on business trips for more than one-third of the year. When doing such work, I often listened to talks in research fields that differed from my own. At first, those speeches had little to do with me, so I didn’t concentrate on listening to them. However, as I took the opportunity to listen, I realized that many parts of those talks could be useful for my research. I learned from such opportunities that listening to researchers in other fields is paramount to developing new research in my field.

Researchers from other organizations are both competitors and collaborators. If you hide all your new ideas and research results just because they are your competitors, your arguments will get nowhere. If you don’t speak, your ideas won’t be stolen; however, by speaking, not just listening, you can build and maintain relationships of trust with your competitors. I think that kind of communication is important. Of course, your research results must be valuable and meaningful to the other party. I want us to build good cooperative relationships in which we can grow and increase our accomplishments, exchange information with other parties, and aim for our next accomplishments.

Researcher = Geek × Olympic athlete?

—Please tell us about the most-memorable events in your research life.

It was when I was researching optomechanics. I am also a visiting professor at Tohoku University. Once, at the university, a student in my laboratory who was involved in research said, “Professor Yamaguchi, I can’t measure it.” When I asked, “What is it that you can’t measure it? Are you doing something wrong?”, the student said, “When I try to measure it, the element trembles of its own accord.” So I said, “That can’t be happening. Try again. Something must be wrong.” When the student re-measured it, a large vibration was indeed generated, and the target could not be measured. However, it could be measured when the conditions were slightly changed. By investigating this phenomenon, we discovered an operating principle of a completely new device related to light, electrons, and mechanical vibration, and published a paper about this principle in *Physical Review Letters*, one of the most-prestigious journals of the American Physical Society. We couldn’t have written that paper if I had overlooked this phenomenon as some error made by a student with poor laboratory skills. It was an event that made me realize that it is really important to have an attitude of valuing even the slightest change, even one by chance. When I thought about it later, the personality of the student who honestly reported the phenomenon to me led to success. If a student who had a different personality had discovered the phenomenon and tried to do something about it alone, the phenomenon might not have been reported. In other words, we should emphasize diversity in regard to the nature and personality of researchers. In many cases, we can only progress by working with researchers with different characters and perspectives.

I think researchers are “geeks,” very unique people. The average person may wonder, “Why is something so difficult so much fun?” For people like us who are absorbed in physics, however, we enjoy delving deeper into difficult research. In a sense, we research in a world of geeks. On the contrary, I think that researchers also have a characteristic similar to that of an Olympic athlete. Unsatisfied with becoming the top in their respective countries, they are competing for the top on the world stage. Olympic athletes may also be geeks in the sense that they are pursuing their sport. In any case, people are happy to be able to pursue what they like. However, researchers face a lot of hardship and are constantly under pressure since compromises are unacceptable, and matters must be investigated thoroughly. We are competing with researchers from all over the world aiming for the top, and some young researchers may feel crushed by that competition.

—Please say a few words to junior researchers.

There will always be times when you feel like you're about to get crushed or you don't get the results you expected. As you gain experience, you'll gradually get used to such times. When I joined the company, I sometimes didn't see the fun in the research theme assigned to me. Therefore, I talked to my boss about my distress that things weren't going well, and although I got involved in another research, the results of that research were unsatisfactory. At that time, I realized that I had focused too much on showing my own characteristics in the research theme that I wasn't confident with. Throughout this experience, I was blessed with a very caring boss, and I began to tackle themes that seemed uninteresting head-on. Then, I gradually felt that those themes were interesting. The Japanese proverb, "Three years on a cold stone will make the stone warm" means that perseverance and patience will bring good results, and now I know it really does. Therefore, I think it's better to move on a track laid for at least three years even if its direction seems different from that in which you are willing to go. I understand that researchers tend to avoid choosing themes that other people can do since they value being unique. However, once you've gained experience, you'll be able to conduct your own research; that said, just start from the theme you are given. Over time, your unique ability will surely emerge.

Moreover, those who manage basic research teams may feel pressure to be leaders; regardless, I think it's important to leave outstanding researchers alone. That is, managers should let researchers do what they want to do and dedicate themselves to supporting those researchers. Managers may feel anxious if they do not give direct guidance to researchers; however, I think we should foster the independence of our young researchers. It might be necessary for young researchers to try to free themselves from the customs of Japanese society that they have been brought up on, i.e., being provided every possible support. You may be concerned about the future, but today's research environment in Japan has a higher degree of freedom than in the past, and I think you will get many opportunities to play an active role. Let's enjoy our research together.

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■ Interviewee profile
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He received a B.S. and M.S. in physics and a Ph.D. in engineering from Osaka University in 1984, 1986, and 1993. He joined NTT Basic Research Laboratories in 1986. His current interest is in micro/nanomechanical devices using semiconductor heterostructures. He has been a guest professor at Tohoku University, Miyagi, since 2006. He is a fellow of the Institute of Physics and the Japan Society of Applied Physics and a member of the Physical Society of Japan, the American Physical Society, and the Institute of Electrical and Electronics Engineers.