Creating a Map of Science and Connecting with the World and Future through It

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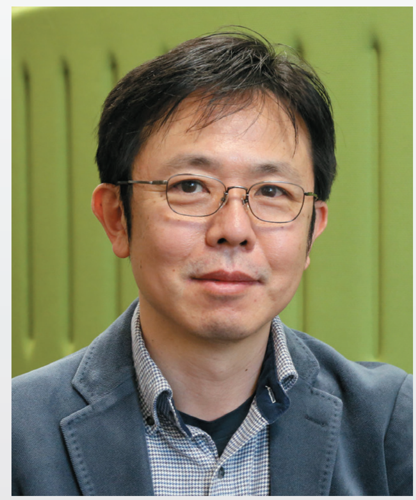


Abstract

Researchers at the Quantum Solid State Physics Research Group of NTT Basic Research Laboratories focus on the many-body and correlation effects caused by the interaction between electrons as well as on quantum-mechanical properties of electrons such as wave nature, superposition state, and spin. By engineering and controlling these properties of electrons using the heterostructure and nanostructure of semiconductors and atomic-layer materials, the group is investigating quantum devices and sensing techniques that cannot be obtained with individual electrons. Such research is expected to enable the development of ultralow-power-consumption devices and highly sensitive sensors. We asked Koji Muraki, a senior distinguished researcher and leader of this group about the progress of his research and the attitude researchers should have.

Keywords: topological insulator, quasiparticle, semiconductor heterostructure

Quantum correlation brings out the potential of electrons

—Please tell us about your current research.

My research aims to obtain physical properties not found in conventional semiconductors and new functions exploiting such properties by using (i) a structure in which different types of semiconductors are artificially laminated (i.e., *heterostructure*) or (ii) a microfabricated structure (i.e., *nanostructure*). In particular, I'm focusing on the quantum-mechanical properties of electrons, especially a property called *spin*, i.e., having magnetic properties of small magnets, and the *many-body effect*, which is caused by a large number of electrons acting as a group rather than moving around independently.

We are pursuing such research of physical phenomena to engineer and use the properties of electrons that are not used in conventional devices to enable the development of ultralow-power-consumption devices and highly sensitive sensors. Our ultimate goal is to create a quantum computer based on a new operating principle that overcomes the weakness of a conventional quantum computer, i.e., the quantum state changes due to noise (i.e., low error tolerance) (**Fig. 1**).

We are taking two broad approaches to this research. One approach uses the many-body effect

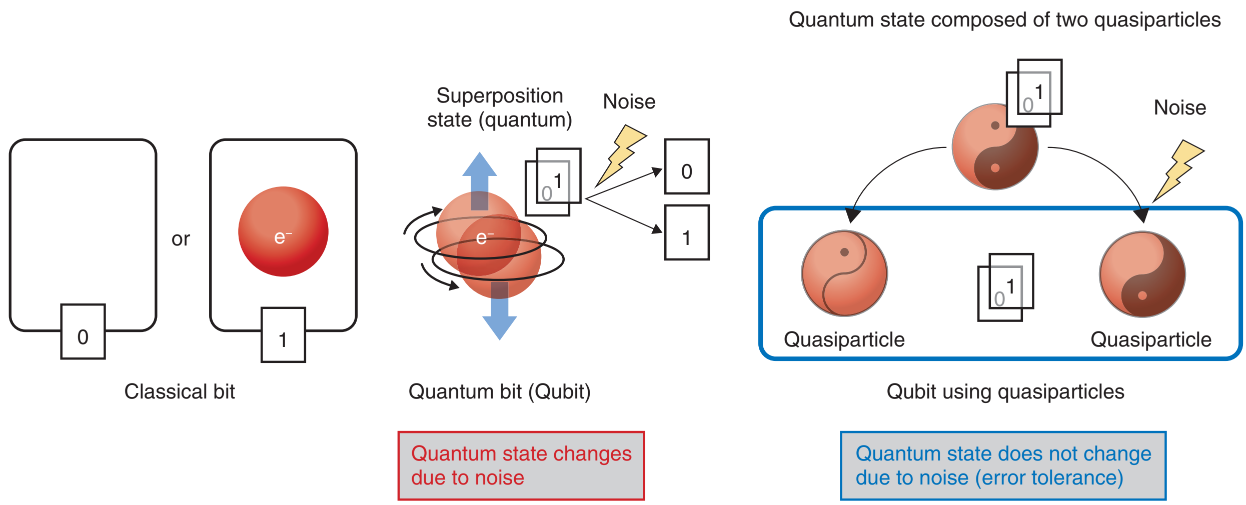


Fig. 1. Quantum bit using quasiparticles.

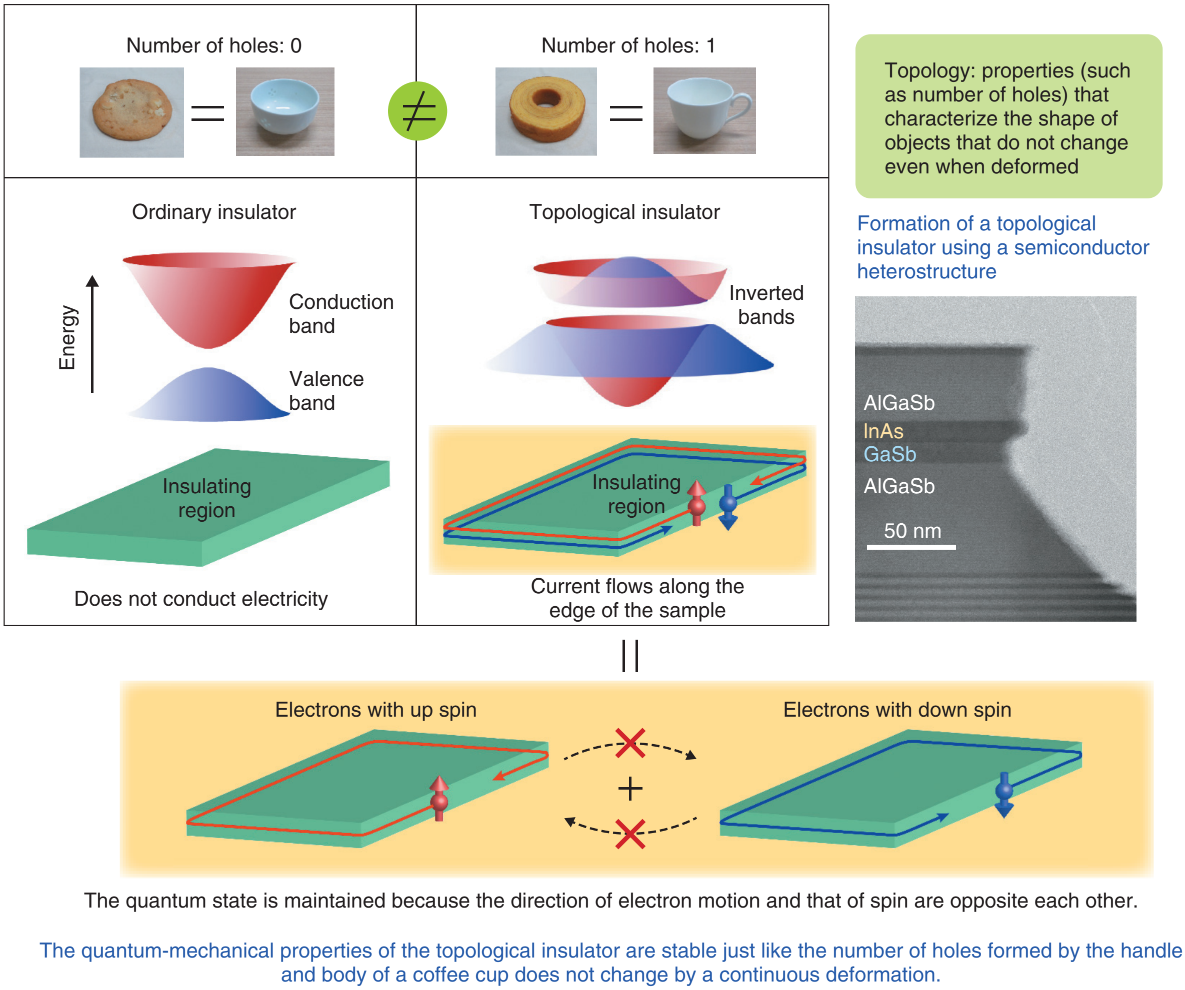
that I mentioned above, and the other relates to spin and uses a new kind of material called a *topological insulator*.

Before explaining the approach using the many-body effect, I need to explain the so-called *quasiparticle*. For an example of a quasiparticle, let's take a look at a p-type semiconductor, which is a transistor component. If electrons that are negatively charged are missing in the semiconductor's energy levels that they are supposed to fill, those states, called *holes* (because they look like holes from which the electrons have escaped), behave like positively charged particles. Such holes have essentially the same properties as electrons. Our goal is to create quasiparticles with properties that are essentially different from electrons by exploiting the many-body effect.

The other approach is to use a topological insulator. The concept of topological insulator was first proposed in 2005 and is a very new concept in the history of physics. The 2016 Nobel Prize in Physics was awarded to the three physicists who created the theory underlying topological insulators. An insulator is a material that does not conduct electricity. According to the theory proposed in 2005, there are two types of insulators: topological insulators and ordinary insulators, and a layer that conducts electricity always exists at the boundary between the two types of insulators. In 2013, our group experimentally demonstrated that a topological insulator can be formed using a heterostructure of semiconductors [1] (**Fig. 2**). Although various materials have been reported as topological insulators, the topological insulator created using our semiconductor heterostructure can be electrically controlled and switched between a normal insulator and topological insulator by applying a voltage to the gate electrode. In fact, we were the second team in the world to experimentally show that this material system (i.e., the semiconductor heterostructure shown in Fig. 2) can form a topological insulator. The first team published a paper showing that conduction occurs at the edge of the system, and we took time to expand on that paper and showed that the system *is* a topological insulator, that is, it does not conduct electricity excluding the edge of the system. Our paper is still often cited, but being number two made me think about how to present our results.

—You were interviewed eight years ago, and you've achieved numerous results since then.

That interview [2] eight years ago was just after the results of an experiment using a method called nuclear magnetic resonance to show that the spin of electrons under special states are aligned in the same direction due to the many-body effect. The resulting paper was published in Science in 2012 [3]. Since the direction of the spin determines whether the electron can occupy the same position, the paper was highly evaluated as indicating that the electron is in the *special state* predicted by theory. In 2014, using nuclear magnetic resonance once again, we demonstrated that under different conditions, the electrons form a lattice like a crystal and become immobile, and that paper was published in Nature Physics [4]. Although



Al: aluminum
InAs: indium arsenide
GaSb: gallium antimonide

Fig. 2. Formation of a topological insulator using a semiconductor heterostructure.

this paper was published because it was seen as new experimental evidence supporting the long-held phenomenon known as *electron crystallization*, it was not fully satisfactory for us in regard to the original purpose of clarifying the properties of quasiparticles.

Up until that time, I had been investigating the nature of electrons that form the background, or matrix, of quasiparticles; however, more-precise measurement techniques for investigating the properties of quasiparticles have become necessary. Therefore, I invited a researcher at a university to join my group who was interested in the same topic and had the necessary skills and knowledge. Until then, my research style had been to carry out every procedure by myself from sample preparation, measurement, and theoretical analysis; however, I thought I shouldn't keep doing that. For example, the charge on a quasiparticle is smaller than the charge on an electron, and the number of research groups in the world that can measure it is limited. As reported in a recently published paper, by combining nuclear magnetic resonance and quasiparticle-charge measurement, we were able to clarify how the electronic state changes when an electric current is applied. That idea came from a member of my group, not myself.

The next step after forming a topological insulator with a semiconductor heterostructure is to control it electrically; however, this step also faces a problem. That is, an insulator was formed only under very limited conditions, and that limitation was inconvenient in regard to conducting various experiments. Therefore, by intentionally incorporating materials with the different lattice constant and using the strain in a crystal, in 2016, we were able to improve the properties as the insulator, and in 2020, it became possible to switch between topological insulators and ordinary insulators electrically while maintaining the insulator properties. These accomplishments required a steady accumulation of experiments, such as crystal growth and improvement of the gate insulating film, and those who worked hardest were the young researchers in the group. Although it is now known that various materials are topological insulators, no one has achieved the expected results with regard to the spin properties of the edge of an insulator, and we believe that a real breakthrough will be achieved in the future.

Researchers have no apprenticeship period

—In regard to your research activities, what do you feel has changed since the last interview?

At that time, I was working with a small team consisting of a postdoctoral fellow (a researcher in a limited-term position after obtaining a doctoral degree) and two or three other researchers; however, the number of members involved in the project has now increased. It's my responsibility to coordinate shifts so that young researchers can conduct experiments while taking measures to prevent the spread of the novel coronavirus and support them so that they can devote themselves to research. It is the younger members of the group who are directly involved in challenging experiments.

As a result of the change in my position, I sometimes feel it frustrating that I have less chance to directly engage in experiments. For example, if you're experimenting by yourself, you're the first to see the results; in contrast, when you are working in a group, young researchers conduct the experiment, so they will see the experimental results first. By the time I get to know the research results, a process by which the group members notice something about the results and report it to me had been added. In other words, the results I received had been filtered by other researchers. However, that change is not such a bad thing because other group members can notice things that I might not notice, and the group can achieve results that cannot be achieved with just one person. In consideration of the fact that the members bring proposals and ideas that cannot be thought of by oneself, their contribution is overwhelmingly greater than any amount of my frustration. I feel that I am working in a very blessed environment.

In a position to manage the group, I think it is important to make use of the abilities of individual researchers with multiple interests and specialties so that they can move in the right direction both individually and as a group. Since researchers will not be enthusiastic about a subject they are not interested in, I think it is essential to create an environment in which each member of the team can do what they want to do. For example, even if you can produce results when doing something other than what you want to do, you won't be able to continue producing results in that way. I think unless you feel that you are the one who produced the result or you think nobody else could have produced the result, you won't get a true sense of accomplishment.

What's more, I think that many people who produce results are good at building relationships based on trust with those around them and can collaborate with them. Just because you think about managing a group does not mean that the group will produce good results. However, we are currently able to come up with ideas without hesitation under very good relationships based on trust, so I believe we can continue to produce good results.

—Has there been any change other than research activities during the stay-at-home request period to prevent the spread of novel coronavirus infection?

My passion for the electric guitar, which was my hobby when I was a student, has rekindled. I hadn't played it for a long time, but I revived it while I was staying at home after the state of emergency was declared in April 2020. The electric guitar does not feel right to play unless it makes a loud sound from an amplifier. One reason for my renewed interests is that thanks to digital technology, I can feel as if I'm playing at a loud volume in a concert hall just by generating sound in my headphones. Moreover, many channels on an Internet streaming site host my favorite guitarists explaining how to play, and others allow amateurs to show off their performances. The feeling of being able to connect with people around the world through being interested in the same things is similar to research.

However, research has a special aspect. In the case of music, everyone starts out as an amateur, and only a handful of them become professionals. In contrast, as soon as a researcher becomes a member of a laboratory, they will be treated as a full-fledged researcher and required to present their research results in papers and at academic conferences. If you have a job in which you also write articles, like a newspaper reporter, I imagine that no matter how many articles you write, they may be turned down by the chief editor and not published in the paper. However, if you are a researcher, you will be required to publish your research results in the form of papers, unless you turn them down yourself. As I said in the last interview, researchers suddenly become professionals without an apprenticeship period or rehearsals.

What I realized this time is the research environment of researchers differs depending on the institution to which they belong, such as companies and universities. For example, researchers at universities will spend more time acquiring research funding than corporate researchers. As a researcher at a company, I realized that I was fortunate to spend less time acquiring research funds than researchers at universities. I thought that that's why I had to discipline myself and put more effort into my research. Sometimes it is important to look at yourself objectively like that and confirm the value of your existence.

I want to achieve results for which it can be said "That was a breakthrough."

—Confirming the value of existence has a philosophical sound. How do you see the work of a researcher, Dr. Muraki?

I think that researchers are self-fulfilling through their research and have the joy of connecting with the world and strangers through research. Through research, we create a map of science and connect with the world and future through that map. If I recall correctly, I also mentioned in my last interview that the work of a basic researcher is to make a *map* and that making a map is an adventure; I haven't changed that way of thinking. Unless your research results were incorrect, you should be able to trust the map you made. Even if the map (research) you are working on is not directly useful, it will be useful in some way. I think that that map can be left to posterity.

However, the way we pursue adventure has changed a lot from eight years ago. Currently, our junior researchers are actually conducting experiments, and I'm in a position to ask questions and give advice based on their results. Although we're going through this adventure together, it's clear that I'm actually less likely to see the results with my own eyes or touch them with my own hands. On the contrary, it is fun to learn from junior researchers, and I'm happy that such opportunities have increased. I want to work with young people doing work for which we can say, "That was a breakthrough."

—Please give a word of advice to the next generation.

When talking to young researchers at academic conferences, it can be overwhelming to find people who are familiar with not only the current state-of-the-art research but also the research done before they were born. I think it's a privilege for young people to be able to study thoroughly what they are interested in. Of course, I'm researching what I'm interested in too, but how much time and energy I can devote to one research topic is far from what young researchers can do.

I think that most young researchers, with a few exceptions, always have a feeling that they can't do what they want to do, don't produce good results, don't seem to be recognized, or feel gloomy. However, those feelings always accompany the privilege of youth, so I want you to concentrate on making the most of that privilege. It would be unworthy of you to worry too much and do not do what you want to do. That is why I want you to broaden your options and cultivate negotiation skills to open up your path.

I recently noticed that there are cases in which younger generations who used to be trainees or postdocs at our laboratories have achieved great results after they had their own research groups and various careers. I think that although their careers as researchers were not plain sailing, the fact that they have diligently accumulated results and built a solid platform over a long period has paid off. Looking at these people, I once again feel that the life of a researcher is pretty long. What they all have in common is an attitude of not giving up.

To live as a researcher, it is important to have the *depth* to delve into what you are interested in and the *width* to observe broader areas. I also want you to take an *exit-oriented* approach striving for the results you aim for in addition to an *entry-oriented* approach focusing on research themes. Many basic researchers may be entry-oriented, but you should continue to dig from not only one side of the *entrance* but also from the *exit* while exploring various possibilities. The idea of digging at various places from *both sides of the tunnel* may be effective in the long run. Therefore, let's listen to the opinions of a wide variety of people to expand our possibilities.

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■ Interviewee profile

Koji Muraki

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He received a B.E., M.E., and Ph.D. in applied physics from the University of Tokyo in 1989, 1991, and 1994. He joined NTT Basic Research Laboratories in 1994. From 2001 to 2002, he was a visiting researcher at the Max Planck Institute for Solid State Research, Stuttgart, Germany. His research interests are focused on the many-body effect in low-dimensional semiconductor structures. He is a member of the Physical Society of Japan and the Japan Society of Applied Physics.