A carefree boyhood surrounded by nature's abundance

— What was your boyhood like?

I was born in Ohira Village, Miyagi Prefecture. It is a farming village located on the Sendai Plain, and is the only "village" in Miyagi Prefecture. A Toyota Plant has been built there and the village is now financially better off than the neighboring towns. But it is still a "village."

Ohira Village is unusual in that approximately half of its area is owned by the Ministry of Defense (Japan), and a Self Defense Forces maneuver training field is located near the elementary school. During class, we often heard the sound of cannons and the engines of fighter planes. It might be due to these experiences that I have an affinity for airplanes.

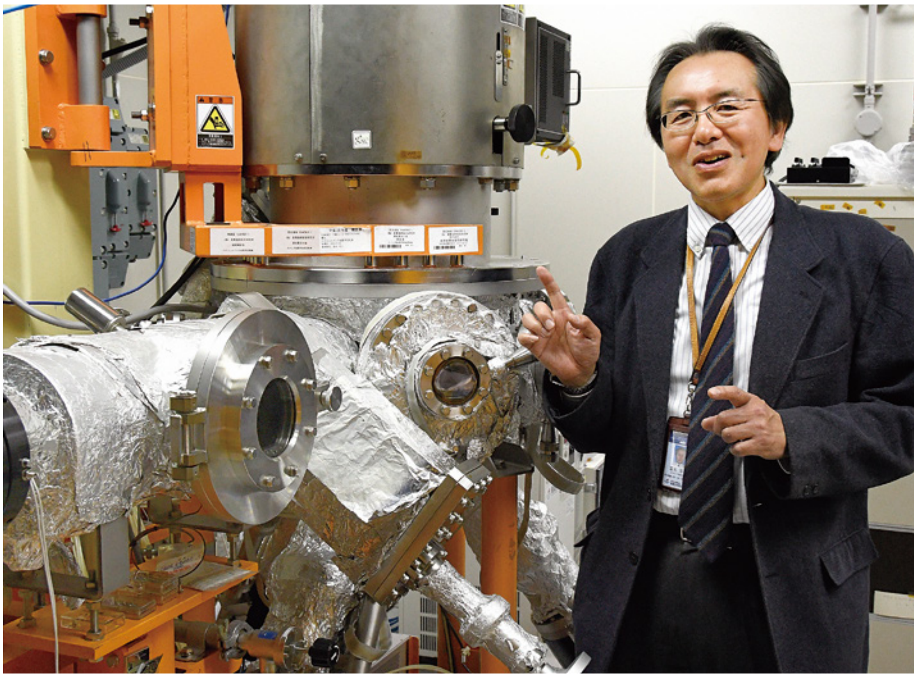
All through elementary school and up to seventh grade, I was so absorbed in the abundance of nature surrounding me that I hardly studied. In summer, we used to dam up a river and use it as a swimming pool. In autumn, you could see a lot of dragonflies flying around. The rice paddies and reservoirs were full of frogs, which we caught and played with. I often dug up potatoes in the fields, too.

When I was in fourth grade, our family moved to a neighboring town (Taiwacho). This was the town where the movie "The Magnificent Nine" (distributed by Shochiku Company Limited), which

Junji Tominaga, Ph.D.

He received his PhD from Cranfield Institute of Technology (now, Cranfield University), UK in 1991. Since 1991 to 1997, he had engaged in the research and development of optical phase-change memory discs (DVD-RAM and DVD-RW) in TDK corporation. In 1997, he left TDK, and moved to National Institute of Advanced Industrial Science (AIST) as a senior staff of the advanced optical memory project using near-field optics. He was the former director of Center for Advanced Near-field Optics Research (CAN-FOR) until 2009. Now he is a prime senior researcher of AIST, and has engaged in nonvolatile electric memory using phase change materials, and topological insulators.

He received The ministry of economy and industry award (1999), Japan IBM award (2000), S.R.Ovshinsky award (2014) and Honda frontier award (2016).



National Institute of Advanced Industrial Science and Technology (Japan)
Nanoelectronics Research Institute Department of Electronics and Manufacruring
Junji Tominaga, PhD, Prime Senior Researcher

Phase-change Memory Research in Which Any Point Reached Marks a New Starting Point

—— Research policy taking a unique point of view with the motto, "We can do it if we try"

The phase-change memory developed in the 1960s is based on a technology that records differences/changes that occur between crystallized and amorphous states of the same material. This technology had been overshadowed by magneto-optical (MO) technology until the 1990s. However, with the commercialization of blue lasers, the requirements for ultra-high density memory increased, which suddenly sparked greater interest in phase-change technology. Dr. Junji Tominaga, a Prime Senior Researcher at the National Institute of Advanced Industrial Science and Technology who is featured in this issue of Vision, has been researching phase-change technology since the 1990s. His research results first led to the development of phase-change CD-RW and Blu-ray compatible ultra-high density DVC-RW disk media, and then to the creation of many wonderful devices, such as the superlattice energy-saving phase-change memory, which he devised essentially on his own. He is currently working on finding practical applications for topological insulators, which hold new possibilities for phase-change memory. We asked Dr. Tominaga about his research on phase-change memory as well as related subjects.

debuted in 2016, was filmed. When I was in elementary school, I enjoyed drawing. My drawings were always selected for prizes in sketching contests and I was awarded supplies such as crayons and paints, so I never had to buy them. The other hobby I had was making model planes.

When I was in ninth grade, instead of studying to prepare for the high school entrance exam, I was secretly focused on studying to obtain an amateur radio operator license, without my parents' knowledge. I did not study my school subjects much, but I was good at math and science. I also liked history.

When I entered high school, I really began to enjoy math and physics. I formed a physics club and was active in it. Since it was not an official club, the school did not give us any money. So I used my own spending money to cover expenses for physics experiments.

One of the devices we made was a sunlight-collecting furnace called a solar furnace. We bought aluminum plates and built something resembling a parabolic antenna after making calculations that would allow us to focus the sunlight on a single point. At a subsequent presentation, we made 1 liter of water boil in 10 minutes.

Following my studies in England, I began research on phase-change technology when magneto-optical technology was the mainstream.

— Is it true that you first joined a private corporation?

After getting my master's degree, I joined TDK's R&D Laboratory in 1985, where I started out working on hard disk research. After about two and a half years (in 1987), TDK's foreign study program sent me to study at Cranfield Institute of Technology in England. During Japan's rainy season, the read-write heads (flying heads) of hard disk systems often broke down due to moisture. TDK decided to send me to England to find out why this was happening.

The Cranfield Institute of Technology that existed when I was studying there cannot be found on maps. That's because an Air Force facility was also present at the Institute. There was a 2,400-meter runway on which even passenger jets could land. I got my PhD at the Institute. I had many wonderful experiences studying in England, and it is not an overstatement to say that my career as a researcher began there. Therefore, I actively encourage the staff at my laboratory to study abroad. Learning about cultures that are different from Japan's and forming new networks can become assets in the future. I send my staff out, telling them just to enjoy life in foreign countries.

Dr. Tominaga (second from right) with his academic advisors at the Cranfield Institute of Technology in England.

When I was finishing my studies in England, the Japanese yen abruptly began to appreciate because of the Plaza Accord, and this caused the hard disk business in Japan to shrink significantly. TDK also withdrew from the hard disk business, except for flying heads, and asked me to work on magneto-optical discs. However, judging that it was too late for that technology, I decided to work on phase-change technology in 1990 and started with research on phase-change CD-RW.

The Magneto-optical (MO) Group had 40 researchers, but my Phase-change Research Group started with just me. The people in the MO Group used to tell me that phase-change technology would never end up producing any products. However, the golden days of MO discs came to an end within a short period. This was mainly because the market around 1994 began to demand a gigabyte class of high-density media in order to handle images.

Just around then, a major debate started over whether to use phase-change or magneto-optical technology for DVD-RAM. A heated controversy was taking place between companies pushing MO and those pushing phase change. It turned out to be a decisive battle. The phase-change camp won in the end.

Changed by a chance meeting with Prof. Tonegawa in an airport

— How did you come to join a specialized research institute?

Prior to commercialization of phase-change discs, I was told by my company to go to the U.S. to present our research results and introduce our new product.

After finishing business in Boston, I was waiting for my flight to New York, my next destination. Prof. Tonegawa happened to be sitting in the seat in front of me in the departure lounge. Since he had just received the Nobel Prize and I was a fan, I decided to ask for his autograph. There was still about an hour before our flight, so I had time to chat with this senior researcher.

Prof. Tonegawa said, "So you've been doing research at a private corporation. It might be time for you to consider going higher."

After returning to Japan, I happened to notice in an academic journal that the National Institute for Advanced Interdisciplinary Research (present-day National Institute of Advanced Industrial Science and Technology (AIST)) was accepting applications for research positions. I sent in my application, thinking that I wanted to pursue phase-change technology all the way. Since the new product that was the result of my research had just been completed, it was a good time for me to take on another challenge. That comment by Prof. Tonegawa in the Boston airport served as the impetus for me to take on new challenges for 22 years after joining AIST in 1997.

Development of ultra-high density optical recording disc using a GST ternary alloy

— We understand that after you joined the Institute, you produced one new result after another.

I was one of two researchers hired through the application process. There was a third researcher who had come from the former Electrotechnical Laboratory. So with a secretary, there

■ **Explanation of a Stirling engine model**

The lower part, which is equivalent to an electrode, is a cup into which hot water is to be poured. Pouring hot water into the cup is the same as applying an electrical current. This switches the phase-change film. Think of the piston as a Ge atom. It is going up and down now, isn't it? This movement of the atom is applying work to the outside. In other words, entropy is being discarded. This is the same principle as that used for switching in phase-change memory. The author of the technical paper had thought about merely adding heat. He missed the point. The upper area is at room temperature and the heat difference from the bottom vessel causes the movement. The upper area can be used for dissipating heat.

were four of us. We were given a newly-built research wing. Over the next 6 to 7 years, we filled the wing with equipment and people.

Research back then was focused on ultra-high density optical recording using phase change. Since light is also a wave in terms of characteristics, it is not possible to focus all of it onto a single point. Also, since waves are subject to a principle called diffraction limit, only 1/4 to 1/3 of the wavelength can be focused. So we began researching a super-resolution technology that would use a solid film and open a light window in response to heat instead of light.

We used a ternary alloy consisting of antimony (Sb), germanium (Ge), and tellurium (Te). This was in 1999. For this research, we received the Minister Award from the Ministry of International Trade and Industry (present-day Ministry of Economy, Trade and Industry), and we also received an award from IBM in 2000.

Next, in 2009, we developed a Blu-ray DVD disc with 4X density using optical super-resolution technology. We gave a demonstration of this disc at the Kyoto Office of Mitsubishi Electric Corporation. We set up four high-definition TVs and the ultra-resolution DVD disc we had developed, along with a single Blu-ray light source, and we succeeded in projecting four images simultaneously on the four TVs.

The wavelength was 400 nanometers and the resolution was 60 to 80 nanometers. Since the current Blu-ray resolution is 140 nanometers, we were successful in projecting images with four times the current density simultaneously on four channels. The images we used included scenes of famous places in Kyoto and flowers. I think this 60-nanometer resolution might still be the world's highest among super-resolution technologies.

Incidentally, the Nobel Prize in Chemistry 2014 was awarded for an application of super-resolution technology. It was achieved by research groups in Germany and the U.S., but their resolution was only 90 to 100 nanometers. Our resolution was superior, but they applied the technology to the medical field. When we heard the news of the Nobel Prize award, I commented to our research staff, "We just missed it! Maybe we should have targeted a living organism." If we had worked with a living organism, we might have won the Nobel Prize .... (Laughter)

From a high-resolution phase-change disc to superlattice energy-saving phase-change solid-state memory

— New research themes seem to be showing up one after another in phase-change memory research.

The next thing we worked on was energy-saving phase-change memory utilizing the uniquely conceived superlattice, which used chalcogenide instead of a GST ternary alloy. Until then, I had been working on optical phase-change discs. However, in 2006, someone involved in semiconductor devices came to us and asked us to focus as well on phase-change memory using electricity. That was a catalyst for me. It was very good timing. That was when all companies were beginning to withdraw from optical discs and, following the economic downturn precipitated by the bankruptcy of Lehman Brothers in the fall of 2008, companies began moving their production from Japan to overseas.

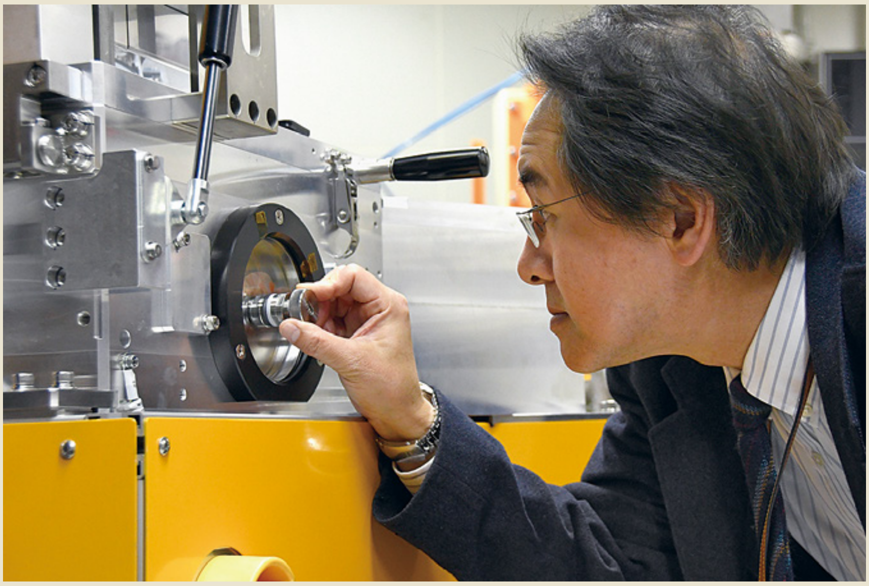
The first step I took was to read technical papers related to electrically switched phase-change memory. One paper included an extremely beautiful device temperature distribution diagram that was color-coded into 1.4 million colors using thermal analysis software based on computer simulation. Although the paper described the results when the maximum temperature was 650°C (molten state) and 200°C (crystallized state), it did not say anything about the instant of phase transition.

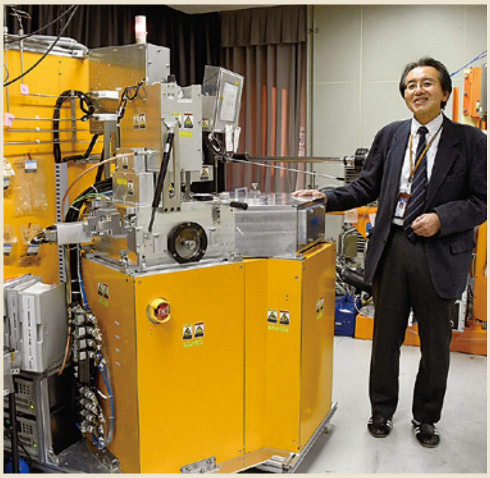
I kept wondering, "Why this omission?" I thought something was wrong.

Phase change means the material goes back and forth between crystallized and amorphous states, repeatedly melting and cooling. It is a heat cycle in which the state is fixed by raising and lowering the temperature. This is a thermodynamics issue. Thermodynamics is governed by basic laws*, known as the first, second, and third laws.

In other words, then, the paper used only the first law for its argument. A thermodynamic cycle would not work with just that. The paper did not consider how much entropy was being lost within the cycle. That is, it ignored the second law of thermodynamics. Since I specialized in physical chemistry, I was convinced that solving this issue would produce improved results. I thought, I would do it if nobody else was going to do it.

I had also been aware of this entropy issue during the time I had previously worked on optical discs. When I made the actual calculations, I found that 95% of the energy disappeared as entropy, and I knew I had to prevent it from disappearing. Although I could not completely eliminate entropy, my efforts to eliminate this 95% energy loss brought me to superlattice phase-change memory.





Dr. Tominaga with the QAM, a compact sputtering system for thin-film deposition R&D. We use this system for evaluating the majority of our current experiments.

A topological insulator is what I'm working on now.

— So that was not the end of your phase-change research.

Actually, a superlattice in which GeTe and Sb_2Te_3 in crystallized states were stacked reduced the energy requirement of phase-change memory, and I thought that would be the end of it. Because of the Great East Japan Earthquake that occurred on March 11, 2011, I was unable to conduct any experiments for a while, so I decided to read a variety of technical papers. I ran into the strange term "topological insulator." Then I found out that Sb_2Te_3 is a topological insulator. I became really interested, since the superlattice memory I had been working on used the same material, but at first I could not understand anything from reading. Nevertheless, I felt that there was huge potential there. As the Japanese proverb says, repeated reading made the meaning clear.

Since there was a professor who was researching this subject at the Tokyo Institute of Technology, I decided to visit him to ask for more details. During the visit, he gave me some homework, and when I got home I carried out a simulation. I was able to definitely confirm the phenomenon the professor had described.

The process involved using a magnet to destroy the time-reversal symmetry of electron spin. The device repeated the "set" state, indicating low resistance, and the "reset" state, indicating high resistance. When I brought a magnet close to the device during this cycle, the resistance value surged and got stuck in the high-resistance state, and would not return to the low-resistance state. Thinking that it might have broken, I removed the magnet, and then the device returned to the low-resistance state. I realized that this phenomenon had something to do with electron spin.

So I have started a spin control project and am currently researching topological insulators.

I'm convinced that if we can develop practical applications for topological insulators, they will be welcomed as an important technology in support of the AI and IoT society of the future. (For details, see page 13.)

Agreeing with Yozan Uesugi's famous saying, "Where there is a will, there is a way"

— What is your policy on research activities?

I have just one policy. I am particularly interested in things that others have deemed impossible. I fully agree with the famous maxim by Yozan Uesugi, the feudal lord of the Yonezawa Domain in Yamagata: "If you try, you can achieve it; if you don't, it will never be achieved. It was not achieved because you didn't try." I interpret this maxim to mean that you cannot achieve something if you have already decided you won't be able to, and you can achieve it if you try. My research activities are guided by a philosophy like this.

When you read technical papers in some research field, you often notice issues that nobody has addressed or that have been overlooked. I approach this with the attitude of, "I must solve these issues."

For example, when I moved from TDK to AIST, I began research using light. Rather than just watching a scanning tunneling microscope (probing microscope), which uses proximity field light, I wondered if I could apply this to some mechanism for making things.

Since a probing microscope uses light to view atoms, it has atomic-level resolution. This idea became the starting point for my development of optical super-resolution thin film technology in 2009. Superlattice phase-change memory also uses the same technology.

In phase-change memory, material goes back and forth between crystallized and amorphous (set and reset) states. As I mentioned earlier, there is always some energy loss. I had thought it would be

* **The first law:** The increase in energy inside a system is equal to the sum of the work and heat added from outside. This is the law of conservation of energy, including heat.

The second law: Increasing the thermal energy of a system (moving a system from a lower temperature to a higher temperature) is not possible in an otherwise unchanging system. This is the principle that entropy in an isolated system can never decrease over time.

The third law: The entropy of any given substance is zero at absolute zero (0K). Absolute zero cannot be reached through a finite number of processes. This is also referred to as Nernst's heat theorem.

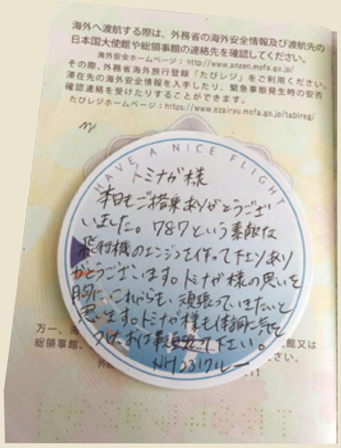
Column (Comment by Dr. Tominaga)

In this colorful age, equipment should also come in bright, fun colors.

QAM, a compact sputtering system for thin-film deposition R&D

For information about the system, visit ULVAC KYUSHU CORPORATION website: https://www.ulvac-kyushu.com/summary/qam/

I really appreciate the fact that ULVAC has been creating excellent systems. However, ULVAC systems are made to look like experiment systems. I asked ULVAC to paint the system to be delivered to us in a special color. Nowadays, even judo uniforms have gone from white to colorful and many other things have become more colorful than they used to be. So I think it's OK to supply colorful systems in fun colors instead of being restricted to the typical factory look. I think women will find these colors more inviting, too. When I went to England, the systems were painted orange. I really liked it. When we specified orange as the color of the first system to be installed here, the person in charge kept asking if that was really OK.



Message from the aircraft captain

interesting to fundamentally overturn this situation, and I developed superlattice phase-change memory with crystal-to-crystal phase transition.

At that time, many people said it could never be done. I thought, who decided that it can never be done? It seemed to me that it had simply never been tried. I think focusing on areas being overlooked by everyone and creating something useful is the mission of researchers.

Never go against nature, just try to fool it.

— Where do you find inspiration?

I get ideas when I'm brushing my teeth in the bathroom every morning. The super-resolution technology I mentioned earlier came to me when I was in the bath. The initial inspiration came when I was bathing my daughter. Since I keep thinking about the issue until inspiration comes, it is more like a direction that emerges while I'm thinking rather than a flash of inspiration. I check the inspiration against various types of literature and theories, but in most cases it requires tricking nature. I learned this approach of "fooling nature" while I was studying in England.

The professor I was studying with specialized in metallurgical engineering and was researching metal fatigue in jet engines and airplane bodies. He used to say, "What technology needs to do is fool nature. If you make something that tries to conquer nature, nature will get even with you. Therefore, do not try to surpass or conquer nature. But if you can fool it, nature will be accepting."

This concept also applies to the entropy issue in my superlattice memory. Maxwell's demon lives there, and you must pay a heat energy tax to the demon whenever you use heat energy. That is nature's law. In other words, you cannot create a heat engine that has zero entropy (the law will not permit a perpetual motion machine). Therefore, we just have to cleverly fool Maxwell's demon.

Enchanted by the sound of jet engines

— What are your hobbies?

My hobby is flying radio-controlled airplanes. On weekends, I'm out doing that. I like airplanes' aerodynamic shapes, which conform to fluid dynamic principles.

At the university in England, I belonged to a group that was developing and researching turbine blades for Rolls-Royce jet engines. The ANA 787 uses a Rolls-Royce jet engine. When I travel on business, I try to fly ANA. The seats are equipped with noise-canceling earphones, but I never use them because I'm interested in jet engine sounds.

One time, a flight attendant came to my seat and said, "If you wear these, they will eliminate the noise and you'll be more comfortable." I said, "I was once involved in researching turbine blades. So I'm very interested in engine sounds, and I'm enjoying them because I can tell the engine is running normally." The attendant must have relayed this to the cockpit. When I was getting off the plane, I was handed an appreciative message from the captain. It said, "With a customer like you riding our plane, we can operate it with peace of mind."

The best time to enjoy airplane engine sounds from Narita Airport is when a south wind is blowing, and the best spot is Sakuranoyama Park in Narita. Since many flights come in between 2:30 and 3:00 PM, that time slot is really good. My favorite spot is the embankment located near Osaka International (Itami) Airport. Planes fly a mere 50 meters above your head. But riding in an airplane is the best. Rather than hearing it as noise, try to listen to it as art. (Laughter)

Japanese companies should forge ahead by merging phase-change and magnetic technologies

— Can phase-change memory and other types of memory coexist?

What we need to do from now on is combine phase-change memory with MRAM. Using a topological insulator, we can operate memory without using an ordinary magnetic material. We will also be able to freely control spin without using a magnetic material. What we need to do in phase change is separate the part of phase-change memory in which a topological insulator is used to control spin from the part of the memory that uses spin, and embed both of them inside a single device. That is the future I'm thinking about. There is no need to eliminate either of these technologies. We just need to proceed on the same path together. I think that will help Japanese companies grow. We need to avoid battles like the one that occurred in the past over optical discs!

Text of a lecture by Dr. Junji Tominaga (excerpted version) given on November 21, 2018
Special lecture "Next-generation Phase-change Memory" (hosted by ULVAC EQUIPMENT SALES, Inc.)

About topological insulators, which are considered very promising in view of an IoT and AI society based on big data

In phase-change memory, which is Dr. Tominaga's research area, it is safe to say that any point reached marks a new starting point. He is currently working on topological insulators for use in next-generation phase-change memory. What does this strange word "topology" mean? We will introduce the possibilities and application fields of topological insulators, to which the topology theory is applied.

The Nobel Prize in Physics 2016 was awarded to the following three people: Thouless, Haldane, and Kosterlitz. These three introduced the concept of topology, which is one of the geometric theories in mathematics, and discovered topological phase transitions in the basic characteristics of matter. While developing materials at the cutting edge of modern science in the 21st century, scientists all over the world are waging research battles in pursuit of great possibilities.

As part of this, research is underway on topological insulator materials, in which electricity flows on the surface despite the fact that no electricity flows inside.

Tominaga: In the fall of 2010, I had submitted a paper on superlattice energy-saving phase-change memory to a professional journal, and I was relieved that the paper had just been accepted. Because of the Great East Japan Earthquake of March 11, 2011, I could not conduct any experiments for three or four months, so I spent most of my time reading technical papers. One paper said that Sb_2Te_3, which I was working with, is a topological insulator. While I was reading technical papers, the expression "time-reversal symmetry" caught my attention.

So I decided to apply a magnetic field. When I brought a magnet close to an ordinary ternary alloy, nothing happened. But when I brought a magnet close to the superlattice stacked film I had developed, its threshold voltage jumped from 0.8 to 2 V. When I removed the magnet, the threshold voltage returned to its original value. It was a weak magnet of around 0.1 Tesla, but I found that bringing this magnet close to the film changed its resistance value by two orders of magnitude. The change that occurs in MRAM is much smaller. Based on past experience, I had thought that phase change did not exhibit any magnetism. This experiment showed that destroying the time-reversal symmetry would cause some change.

In a topological insulator, the state of its electrons (wave function) is said to be "twisted," unlike in ordinary insulators. An unimaginable phenomenon was confirmed in which this twist prevented electricity from flowing inside the material while allowing it to flow only on its surface.

Tominaga: The $Ge_2Sb_2Te_5$ ternary alloy is an ordinary insulator since it does not have any twist. In other words, there are two faces inside the alloy. Part of it is an ordinary insulator while another part is different.

What about a superlattice? An ordinary topological insulator only has planar electrical conductivity. $(GeTe)_2$ is an ordinary insulator while Sb_2Te_3 is a topological insulator. When these two materials are repeatedly stacked, electricity will flow not only on the surfaces, but also on their interfaces. Since increasing the number of layers will proportionately increase the number of interfaces, we can extract more two-dimensional current and spin current. Furthermore, this can be accomplished at temperatures that are practical for manufacturing instead of at super-low temperatures. It works fine at 470K. I cannot go into detail due to lack of space, but the technical paper in which I published my research results was cited in other papers around 300 times in 2017. There is now global competition to create materials like this.

There are many kinds of memory, and the fastest types are CPU, SRAM, DRAM, etc. Below these, there are storage memory devices, such as optical discs and hard disks (HDs). In terms of processing speed, DRAM is faster than HD by three orders of magnitude. When handling big data, this difference will become a major problem. To solve this problem, storage class memory has emerged. It is phase-change memory.

The great potential of phase-change memory, to which topological insulator superlattices will be applied

- The next-generation phase-change memory will be a superlattice type and will be able to achieve significant energy savings.
- Phase-change memory is ideal for AI chips.
- It will become possible to carry out machine learning using big data and without using DRAM.
- Superlattice films using van der Waals bonding can also be made using sputtering.
- GeTe/SbTe superlattice film is a topological insulator.
- If topological characteristics can be manifested successfully, they can be applied to spin memory in the future.
- Advances in phase-change memory can be expected to be applied to fields beyond memory.