Interview

Integrating spin currents into physics of matter

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An electron has spin which is analogous to rotation, besides electric charge. As there is electric current as a flow of electric charge, there is a flow of spin named spin current. Spin current related phenomena appears in the submicroscopic world, and it becomes possible to use the spin current by progress of nanotechnology. It may become possible, using the spin current, to process a lot of information with less power consumption and to generate electricity by using the heat and sound in environment. "However, in the present framework of electromagnetism and mechanics, which are the bases for such applications, description of the spin current falls out. We incorporate a spin current into the framework, and are advancing the grand challenge of rewriting physics." says Saitoh Group Leader. The measuring method of the spin current was discovered in his lab. for the first time in the world. Furthermore, he has been proving that the spin current can be generable by various methods, such as electromagnetic waves, heat, and sound.

Imperfection in Physics

Eiji Saitoh Group Leader (GL) received his PhD in 2001, and set up a laboratory in Keio University in 2006. "I studied strongly-correlated electron systems in condensed matter physics during my PhD, and studied nanotechnologies during my assistant period. When setting my lab., however, I decided to start something different. While searching a new research theme, I found an 'imperfection' in the framework of physics. The phenomenon we totally missed was the spin current."

Electron has a property called spin, together with a charge. Spin is an angular momentum similar to the earth rotation. The earth rotation generates a magnetic field as a bar magnet. Likewise, to an electron, magnetism is generated by spin. An electron can have only two kinds of spin rotations with settled value namely clockwise up spin and down spin, while rotations of macroscopic matters can be in both ways with different rotation speed.

What is the spin current?

"As electric current is a flow of charge, a flow of spin is called spin current which is a current of angular momentum."

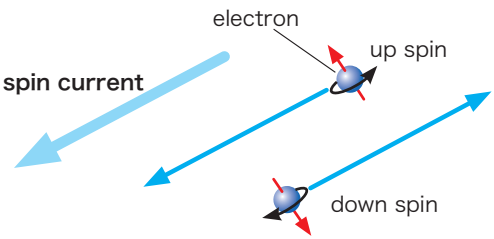


Fig.1. Concept of spin current

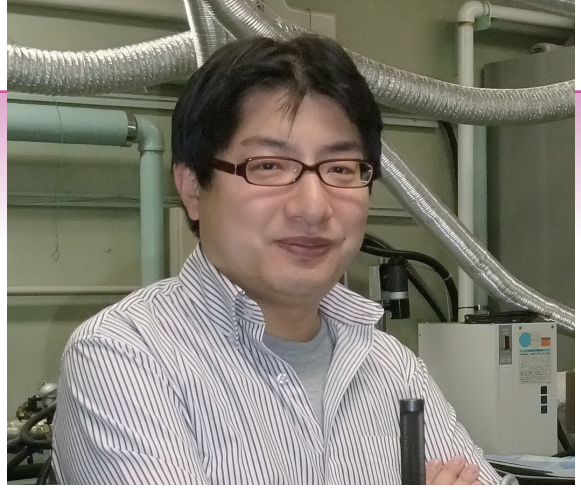
There are some types of spin current. "Conduction electron spin current" (Fig. 1) is one of them. "Considering a metal in which electrons with opposite spins tend to go opposite directions. The charge currents, then, balance into zero, while spin current is finite. That is to say, spin current flows while electrical current does not. This is the conduction electron spin current."

Did you grasp an image of spin current?

"Not to worry if you can't. It is difficult to picture the concept of spin current. Sticking to an incorrect image may rather lead to a mistake in experiment. For now, let us just be aware that a flow of electric charge is electric current while its spin version is called spin current."

In hitherto known electronics, only electric charge of electron has only been used but not its spin. "For instance, the spin current cannot move forward even 1 μm in copper metal. This phenomenon, then, could be ignored when electromagnetism has just been established 200 years ago. In fact, electromagnetism was constructed without spin current, and electronics has been developed accordingly."

In the mid 1990s, however, spin and spin current began to capture attention. "This is due to a development of nanotechnology. Microfabrication in micro and nano scale became possible, and spin and spin current are generated in these scales. In the hitherto electronic engineering, information has been



Eiji Saitoh was born in Tokyo in 1971. After receiving his Ph. D. from the University of Tokyo, he worked as a research associate at the Faculty of Science and Technology, Keio University. He became a professor at the Institute for the Materials Research, Tohoku University in 2009, and has been a guest GL of ASRC since 2010. The fields of experts is the condensed matter physics.

handled by manipulating electricity or magnetism. Massive quantity of electric current is required to enter information in a nano scale area. It is profitable to directly manipulate spin and spin current."

Study of "Spintronics", with intention to use both electric charge and spin began since then. A phenomenon called giant magnetoresistance effect using spin was applied to hard discs in the late 1990s, and capacity of memory increased dramatically.

"I explained that it was necessary to rewrite electoromagnetism and mechanics with incorporating the spin current ten years ago when I set up the laboratory, but only a few people recognized the importance. 'We can do it!! The brand-new world which was totally unexplored was before us.' I was excited. I decided to carry out the research into the spin current."

An electric field generated by a spin current

It is the development of the measuring method of a spin current which Saitoh GL carried out first. "To measure a electric current, we detect a magnetic field, since a magnetic field is produced if electric current flows. Then, what happens when a spin current flows? An electric field is generated. Considering the symmetry of the theory of relativity, it is natural that this phenomenon itself must exist. I gave a proof by experiment that an electric field arise when a spin current passes."

The phenomenon which an electric field is produced by a spin current is called an "inverse spin Hall effect", and Saitoh GL has been awarded many prizes for the discovery. "This phenomenon enabled to measure a spin current by electric current for the first time. Although it was known theoretically that there is a phenomenon of spin current, there was no method of measuring. The experiment of the spin current was attained for the first time by development of the measuring method."

Thermally excited spin current

Furthermore, Saitoh GL advanced research of the generation method of spin current. It was proven that, in 2006, a spin current to be arisen by electromagnetic waves and, in 2008, to be arisen by the difference in temperature of both ends of metals. (Fig. 2)

How temperature-differences can generate spin currents? "It is based on the conservation law of angular momentum. Please imagine a figure skater. A rotational speed will become higher, if their both hands are drawn in while rotating. It is a manifestation of the conservation law of angular momentum."

The important point for spin is that there is only one direction in the precession of spin.

"Since heat itself is random motion of particles, the right rotation and the left rotation will arise at random

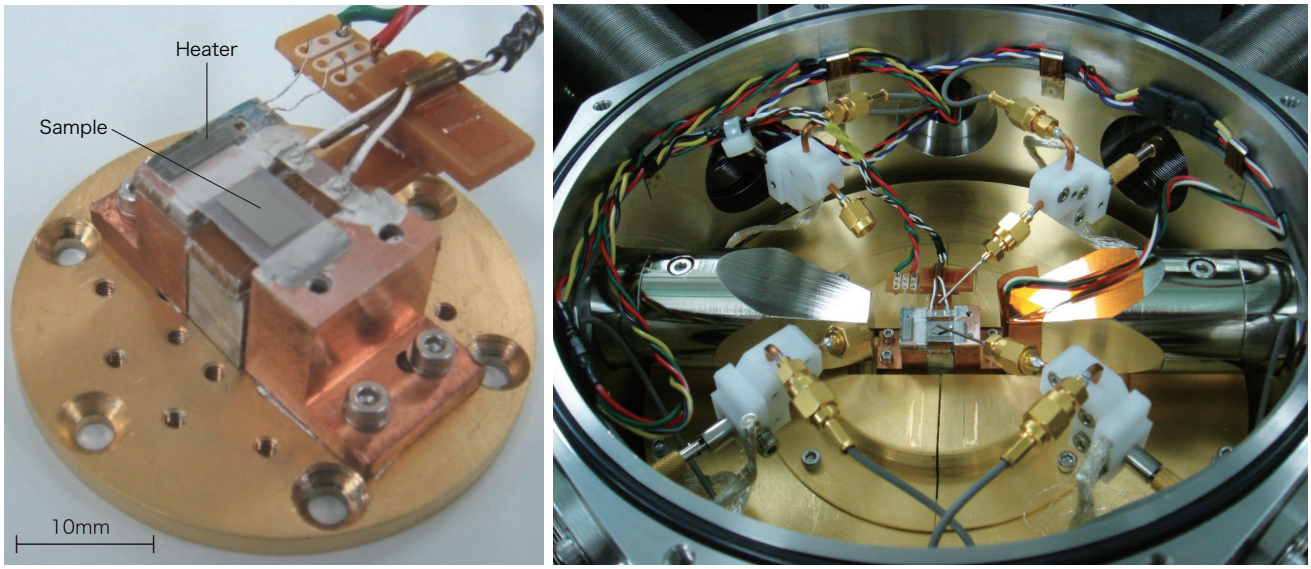


Fig.2 An experimental device generating spin current with heat Spin current is generated by a temperature difference between the both ends of a sample. Other experiments generating spin current in different ways are in progress in similar devices.

in an ordinary substance. However, rotation of a spin is in one direction. There is rectification which changes random movement into fixed movement through the spin. And a spin current is generated compensating the increase of one way rotation with heat by the conservation law of angular momentum."

The spin current generated with heat in this way is convertible to electric current by the inverse spin Hall effect. That is, Saitoh GL and coworkers discovered the new power generation method which builds electricity from heat. "This phenomenon is called the spin Seebeck effect. We did not consider at all that this phenomenon would be appricable for practical use. To convert heat to electricity, the thermoelectric conversion elements made of semiconductors are already in practical use. When this discovery was announced, however, I got a visitor from a certain manufacture immediately."

At present, the thermoelectric conversion elements in practical use convert heat into electricity by the pn junction formed at the boundary between semiconductors called p-type and n-type. "I had thought that the biggest challenge in thermoelectric conversion elements was conversion efficiency. However, the visitor said 'The biggest challenge on converting heat in ordinary environment into electricity is not efficiency but cost.'"

As a future form of an information society, the ambient information society is aimed in which equipments are controlled and useful information are provided by using information collected by small sensors attached into various environment.

"In that case, the visitor says that thermoelectric conversion is the only choice as power supply of the sensors. However, large cost cuts are prerequisite absolutely. For example, in order to generate the electric power to drive a wrist watch using thermoelectric conversion elements of the conventional semiconductor with body temperature, about 60,000 pieces of the pn junctions are required. Since it is necessary to build such a structure into the present thermoelectric conversion elements, the cost is going to be very high. On the other hand, since thermoelectric conversion using spin current does not require such an elaborate structure and utilize the phenomenon occurring in a common material, the manufacturing cost should be able to be lowered dramatically. At the present stage, only 1/100 of the conversion efficiency compared with a theoretical value has been achieved. If the efficiency is improved in the future, however, the thermoelectric devices will be attached on some devices such as a mobile phone and thermoelectric conversion by spin current using body temperature may provide with electric power."

Fig.3 The member of Research Group for Mechanical Control of Materials and Spin Systems, ASRC, JAEA

Spin current realize communication of information even by an insulator

It was also proven by Saitoh GL that a spin current passes through an insulator, i.e., an electric signal can be transmitted in insulator. The big issue of the present electrical engineering in which the electric signal is transmitted by electric current is the energy loss due to the Joule heat generated by electrical resistance. Researches using superconducting phenomena in which electrical resistivity becomes zero are promoted, but it is necessary to cool the material below −100 ℃, even for the material with the highest superconducting transition temperature.

"I have also studied superconductivity once and thought that it is difficult to put the phenomenon appearing only in a limited environment in practical use and to make it spread. Since a spin current is the universal phenomenon occurring in various materials at room temperature, it is very advantageous for application."

By exchanging an electric signal using a spin current, information processing and communication with very little power consumption are realizable.

Spin current of sound wave or rotation origin

Saitoh GL was appointed as the professor of the Institute for Materials Research in Tohoku University in 2009. And he started up his research group in ASRC, JAEA, to research mechanical control of materials and spin systems in 2010. (Fig. 3)

"We are studying the generation of spin current by mechanical motion at ASRC. We are focusing on vibration of a sound wave or rotation motion."

In 2011, Saitoh GL et al. have demonstrated the generation of spin current by vibration of a sound wave. (Fig. 4) The principle enables us to generate electric or magnetic energy from all kinds of materials, such as metals, insulators, magnetic or nonmagnetic materials and so on. The environmental noise converter to electricity on the walls or floors of

the buildings is expected to be developed someday.

"We also want to demonstrate the spin current of rotation origin in a few years. To achieve the goal, we are utilizing the accumulated rotation technique of JAEA."

Rewrite the physics in the next 10 years

What enables Saitoh GL et al. to find new phenomena on spin current one after another?

"We recognized the significance of the spin current at very early stage, and we have been building up the fundamentals of spin current. So, we have great advantages in this research field. Here, we have many ideas for generation of spin current, and only a part of them has been published. So, we'd like to demonstrate the rest respectably by experiments, and to theorize these phenomena."

Saitoh GL told his future prospects as follows, "It is important to complete, taking into account the spin current, the quantum physics in materials overwriting the electromagnetism and mechanics. It signifies the integration of the general relativity into the theory. This approach is very difficult and complicated. We have kept working on it for 5 years with Prof. Maekawa's (present Director General of ASRC) group in the Institute for Materials Research, Tohoku University. We will rewrite the physics in the next 10 years."

The present electronics is based on the law of electromagnetic induction. "We can see the electromagnetic induction not only in special condition but also in usual condition. So, it is a universal and familiar phenomenon. Present electronics has been developed on the basis of highly completed electromagnetism and it supports the basis of our society and everyday life. A universality of a phenomenon and solid theoretical framework are necessary to expand applications."

Saitoh GL emphasizes that a spin current is a universal phenomenon as well as electromagnetic induction. "None of our experiments on spin currents requires a special technology, but nobody had considered the principle of the phenomenon."

How does spin current develope electronics and bring a change into our society and everyday life? "I do not know. It is said that when Michael Faraday discovered the electromagnetic induction in the 19th century, he was asked to explain the usefulness of it and could not find an answer to it. When building the principle of physics, it is almost meaningless to consider whether it will become useful or not. Although we introduced some examples of application using spin current, actual needs or the market of society may not be in sight of a researcher. What we must do is to complete the rigid logical framework of the spin current, and to present the universality and predominancy of the spin current to society with intelligible expressions."

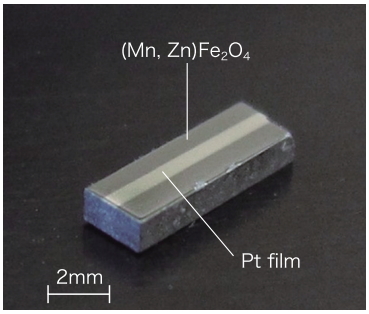


Fig.4 Sample used for an experiment to generate spin current by sound wave
Spin current is generated by vibrating the insulating iron oxide single crystal with sound wave transmitted to it. An electric field induced by the spin current is detected with the platinum electrodes attached on the sample.

For the perfection of physics

"When I was a high school student, I could never imagine that I would be a scientist." said Saitoh GL. "I have practiced the piano since I was 5 years old, and wanted to be a composer in the future. Soon, I left the way and set my face to physics."

How physics attract Saitoh GL?

"That is its beauty. It resembles the beauty of classical music. In classical music, there is architectonical beauty such as harmony and balance, and historic masterpieces of music are logically perfect. Physics also has the perfect nature of a logical system and the laws of physics themselves are beautiful. It can be said for both classical music and physics, training is essential to realize the beauty of them. The both are also alike in their profoundness. The more approaching it, the more I admire the beauty."

"The root of ideas is also its beauty." Saitoh GL continues. "It is worrisome for me that the logical framework of physics which must be perfect contains imperfection. Considering why not being perfect, inconsistency and the defect of the logic become into sight. At the "imperfection" I found ten years ago, spin current was missing. Observing the development of the spin current into the valuable technology, I have come to believe the importance of basic science more than ever."

Interview and writing:

Akira Tateyama, Photon Create Inc.

Translated by ASRC

● References

[1] Conversion of spin current into charge current at room temperature: inverse spin-Hall effect.
E. Saitoh, M Ueda, H. Miyajima, and G. Tatara, Applied Physics Letters **88** (2006) 182509-1-182509-3.

[2] Observation of the spin Seebeck effect.
K. Uchida, S. Takahashi, K. Harii, J. Ieda, W. Koshibae, K. Ando, S. Maekawa, and E. Saitoh*, Nature **455** (2008) 778-781.

[3] Transmission of electrical signals by spin-wave interconversion in a magnetic insulator.
Y. Kajiwara, K. Harii, S. Takahashi, J. Ohe, K. Uchida, M. Mizuguchi, H. Umezawa, H. Kawai, K. Ando, K. Takanashi, S. Maekawa, and E. Saitoh*, Nature **464** (2010) 262-266.

[4] Spin Seebeck insulator.
K. Uchida, J. Xiao, H. Adachi, J. Ohe, S. Takahashi, J. Ieda, T. Ota, Y. Kajiwara, H. Umezawa, H. Kawai, G. E. W. Bauer, S. Maekawa, and E. Saitoh*, Nature Materials 9 (2010) 894-897.

[5] Electrically tunable spin injector free from the impedance mismatch problem.
K. Ando, S. Takahashi, J. Ieda, H. Kurebayashi, T. Trypiniotis, C.H.W. Barnes, S. Maekawa, E. Saitoh, Nature Materials **10** (2011) 655 -659.