Title	Elucidation of spin current caused by properties of the electron as a magnet : pioneering the next generation of electronics by establishing the foundation of physics that controls spin current
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The Research

Associate Professor Kazuya Ando is featured in this issue, whose field of research focuses on spin current of electrons.

Elucidation of spin current caused by properties of the electron as a magnet

Pioneering the next generation of electronics by establishing the foundation of physics that controls spin current

Spintronics is a field of study that investigates into yet unexplored physical phenomena resulting from "spin" – manifestations of quantum-mechanical freedom peculiar to the electron. Highly motivated to make to most of his study for the development of spintronics, Associate Professor Kazuya Ando is devoted to theoretically unraveling spin current which is a focus of attention due to its excellent properties: being convertible to electric current and able to transmit information virtually without energy loss.

Spin is an expression of properties of the electron as a magnet

Dr. Ando's research focus is on physical phenomena caused by what is known as "spin" resulting from freedom peculiar to the electron, which is a field of spintronics.

"While 'spin' is often translated as 'rotation,' it rather refers to the working of a magnet. The electron has an electrical charge; so does it have the properties of a magnet. In the world of quantum, however, spin can take only two directions – upward and downward. Take iron, for example. Iron is ferromagnetic because, with iron the quantities of electrons that have upward and downward spins differ, that is to say, in a state of imbalance. When it comes to gold and silver, meanwhile, they contain electrons with equal quantities of spin whether upward or downward, which keeps these metals from being attracted to a magnet," explains Dr. Ando.

It is usually the case that when a voltage is applied to a material from outside, both an electron with an upward spin and that with a downward spin move in the same direction. This causes the flow of the spins to be offset as a whole and allows only electrical charges to move, generating an electrical current as a result. Conversely, moving two electrons in opposite directions nullifies the flow of electrical charges, thereby allowing only the spin to flow. This flow of spin is what we call spin current.

Of all major achievements in the study of spin current, perhaps the most important is "Giant Magnetoresistance (GMR) Effect" discovered in the 1980s by the 2007 Nobel Prize winners Albert Fert and Peter Grünberg. The GMR effect is observed as a significant change in the electrical resistance that occurs in a thin-film structure composed of ferromagnetic and non-magnetic multilayers, which is induced by spin current. This discovery helped drastically enhance memory capacities of hard disks and other storage media. This phenomenon usually comes out attending on spin current (spin polarized current); from around 2000, it became possible to create spin-only current, which has spurred research endeavors on spin current not accompanied by the flow of electrical charges."

The greatest advantage of spin current lies in that it is free from energy loss due to heat generated by electrical current. This means you can transmit quantum information virtually without energy loss if you only can control the spin current well instead of controlling electron's electrical charges. This is exactly why expectations are high for spintronics as a key technology for next-generation electronics.

Spin current and electrical current are convertible to each other

Of many studies on spin current, Dr. Ando tackles the elucidation of fundamental physical phenomena, which is useful for controlling spin current. "One example is a phenomenon called "inverse spin Hall effect." In this phenomenon, a voltage can be observed in the direction crossing the spin current at right angles when the spin current is flowing. It was first observed with metallic materials from 2006 to 2007.

This phenomenon can be understood based on the special theory of relativity presented by Albert Einstein. His special theory of relativity explains wondrous phenomena, such as "The length of a moving body appears to be shrunk" and "Time of a moving clock appears to be passing slowly." Using this theory, we can convert part of the spin to electric polarization. Such relativistic phenomena can be observed in materials – that's the inverse spin Hall effect. To put it simply, a voltage appears as two electrons, each with an opposite-direction spin, are scattered in the same direction and electrons accumulate.

"Similar phenomenon can happen the other way around. In other words, applying an electrical current causes two electrons to be scattered in opposite directions, thereby generating a spin current in the vertical direction. This phenomenon – the spin Hall effect – was experimentally confirmed by several

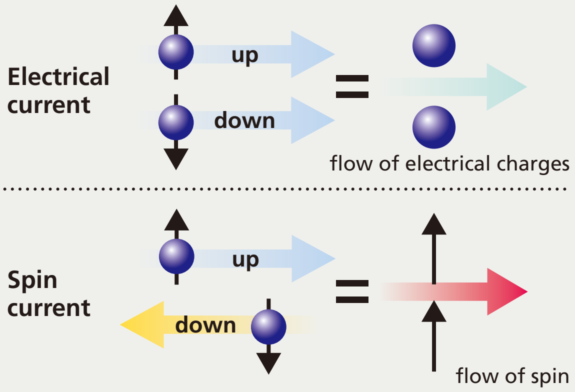

Fig. 1 The flow of "spin"
When an electron with an upward spin and that with a downward spin are moving in the same direction, a flow of electrical charges is generated – we call it an electrical current. On the other hand, if these two types of electron are moving in opposite directions, a flow of spin is created. Such a flow of electron spin is called spin current.

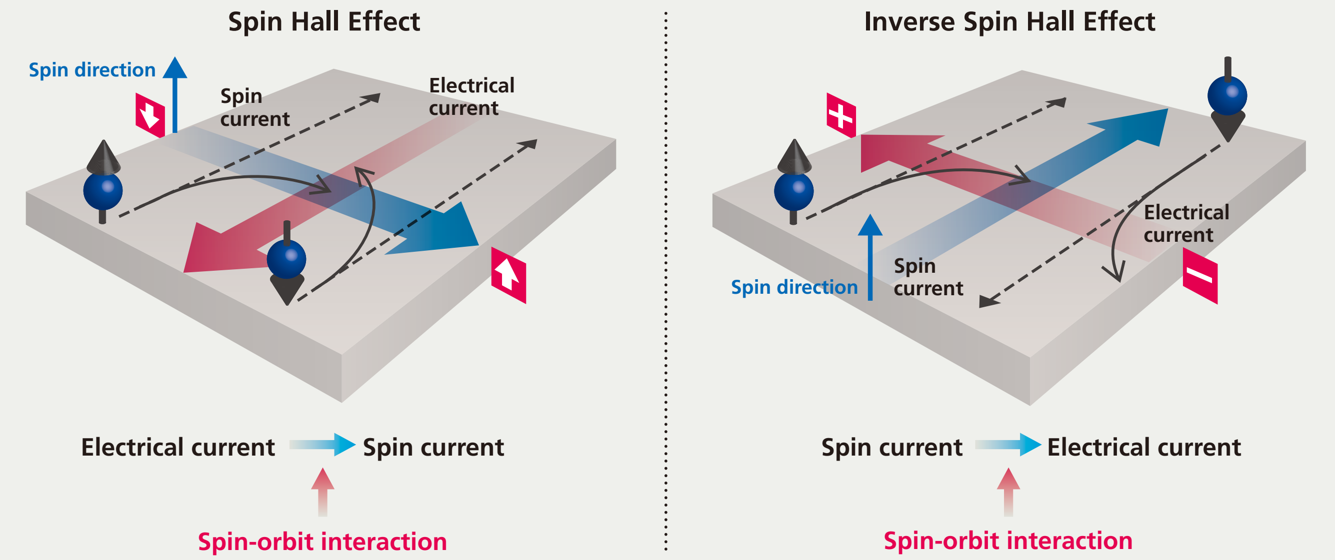

Fig. 2 Spin Hall effect and Inverse spin Hall effect
Due to relativistic effects taking place inside a material, movement of electrons involves a deviation that is subject to spin direction. The relativistic effect that occurs when an electric current is applied to the material refers to the spin Hall effect, while the phenomenon of an electrical current being produced from spin current refers to the inverse spin Hall effect.

groups almost simultaneously in 2004."

Spin current studies began to accelerate at an exceptional pace as theoretical attempts were made to unravel these phenomena and thereby made it possible to create spin currents without using magnetic bodies and to convert spin current to electrical current and vice versa. Based on such knowledge, Dr. Ando is meeting ever-progressing challenges of research themes, such as trying to enhance the conversion efficiency between spin current and electrical current (the current rate being only several percent) and to control relativistic effects taking place on the interface between materials.

Spin currents in various types of material

Of a variety of research themes undertaken by Dr. Ando, worthy of special mention here is the study on a kind of particle called the "magnon" resulting from spin fluctuation.

He remarks, "The fact is that spin current can be generated even when an electrical charge is not flowing. To put it another way, spin current flows even within an insulator. What is responsible for the spin current in the insulator is magnons, or spin fluctuation you might say. With quantum mechanics, it is possible to regard fluctuation (wave) as particles. As such, magnons can be viewed as behavior of particles in a spin wave. Thanks to this characteristic, magnons enable information to be transmitted in insulators."

With conventional information processing based on electrical current, electrically conductive materials, like semiconductors, were needed. But if information processing becomes possible using insulators, the scope of materials that can be used is sure to expand significantly.

Dr. Ando continues: "Furthermore, in insulators, spin current can travel a tremendously long distance of several millimeters whereas in electrically conductive materials it disappears after being transmitted only for several nanometers to several hundred nanometers. Here I'd like to call your attention to another point. On an interface between a metallic material and an insulator, the spin current carrier is converted from conductive electrons to magnons. I recently found that at this point of conversion, the lifetime of magnons holds the key to conversion efficiency." This groundbreaking discovery was published on the December 2014 issue of "Nature Communications."

What's more, Dr. Ando attacks the elucidation of nonlinear physics-related phenomena caused by magnon's splitting/coupling.

"It abruptly occurs that a magnon is split into two or two magnons are coupled; this property differentiates magnons from electrons. I'm attempting to externally control such magnon behaviors and unravel its impact on spintronic phenomena. Once the scope of materials that can be used for spintronics is expanded and we become able to control spin current at our fingertips, it will lead us to greater opportunities for application. The ultimate goal of my studies is to unravel fundamental physics needed by spintronics."

Recently he is also engaged in the study of spin current in organic matters. While efficiency of conversion from electrical current to spin current is relatively low with organic matter, its spin current life is relatively longer – in the microsecond order. Encouraged by this fact, Dr. Ando talks about his eagerness to explore the possibility of organic matters as new materials for spintronics.

"Studies on magnetism have been a field of strength for Japan. And as a key technology for next-generation memories, spintronics is a hot area in which we have so many competitors including businesses. Despite such a competitive environment, I'm highly motivated to open up unexplored fields on my own.

(Reporter & text writer : Madoka Tainaka)

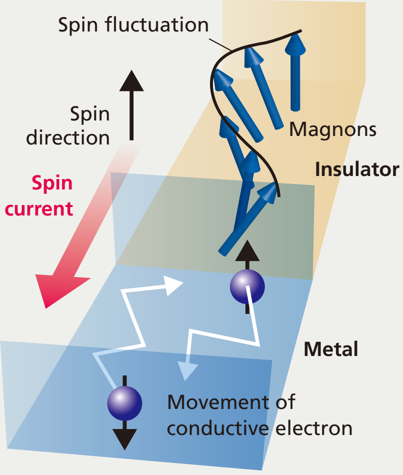

Fig. 3 Conversion of nonlinear angular momentum in solid bodies
On the interface between a metallic material and an insulator, delivery of spin takes place between conductive electrons and magnons. This process enables the spin current carrier particles to be converted on the interface – from magnons to conductive electrons.