The physics of a sustainable society revolution

February 14 2011, By Yoshinori Tokura

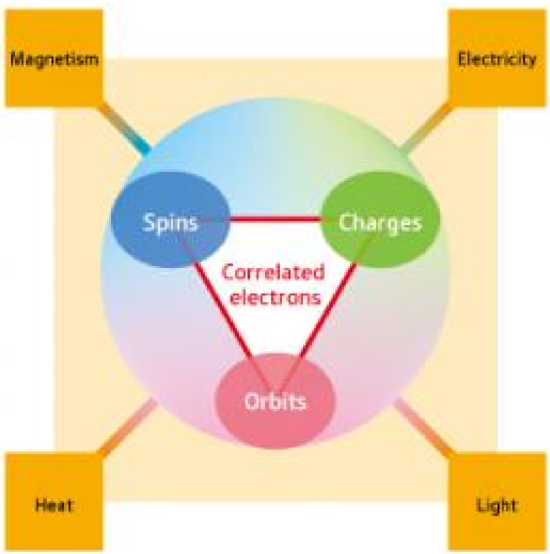

Figure 1: The principle of cross-correlation. By linking electron spins, charges and orbitals using a strongly correlated electron system, it is possible to achieve cross-correlation, an unusual form of responses of electricity, magnetism, light and heat

Faced with global issues concerning the environment and energy and the need to build a sustainable society, we must develop new technologies for generating and using energy efficiently. Yoshinori Tokura, group director of the Correlated Electron Research Group and the Cross-correlated Materials Research Group at RIKEN's Advanced Science Institute, Japan, and his colleagues are working to develop electronic technologies based on new principles to allow information processing to be performed with minimal power consumption and more efficient conversion of light and heat to electrical power.

Innovative physics will lead the way

"I decided to become a scientist when I was a second-grade student at elementary school. Reading biographies of Nobel laureates, I admired scientists for contributing to society through their work. When I was young, the most famous scientists in Japan were the physicists Hideki Yukawa and Shinichiro Tomonaga, who inspired me to become a physicist," says Tokura. "Physics has led to major revolutions in human society," he points out. "A good example is electromagnetic induction discovered by the British physicist Michael Faraday in the nineteenth century."

Electromagnetic induction is the phenomenon by which an electric current flows through a coil when a magnet is inserted into the coil and pulled out again. Its discovery led to the development of power generators, thus laying the foundation for our electricity-powered modern society. Modern civilization is critically reliant on ubiquitous supply of electrical power, all of which has been built on the discovery of electromagnetic induction. "The recent spread of information technology devices, including mobile phones, personal computers and the Internet, has dramatically changed society and economies, and even our lifestyles. This major revolution began with the emergence of semiconductor electronics, with the development of the transistor about 60 years ago. Such breakthroughs are based on physics."

Tokura has a vision for another revolution, which he calls 'Innovation 4'. He believes that four key technological breakthroughs could once again change society as we know it: an increase in solar cell conversion efficiency to 40% or more, an increase in the thermoelectric conversion figure of merit to 4 or more, an increase in the critical temperature of superconductivity to 400 K or well above room temperature, and an in increase in battery energy density to 400 watt-hours per kilogram or more. “These numerical targets represent a tripling of existing performance indexes. Another goal is to achieve electronic information processing with minimal power consumption to conserve energy. If realized, ‘Innovation 4’ will lead to a sustainable society revolution, but it is difficult to achieve these breakthroughs merely by improving existing technologies. We need to develop electronic technologies based on new principles.”

Tokura and his colleagues have been researching electronic technologies based on principles that are totally different from the mainstream semiconductor electronics of today. “It is assumed that electrons are sparse in conventional semiconductor devices, so the entanglement of electrons is weak. A group of many densely packed electrons, however, interact strongly with each other in what is known as ‘a strongly correlated electron system’. In such a system, non-charge properties that are not important in semiconductors, such as electron spin and orbital, also play important roles. We are seeking to create new functions that are not possible using independent electrons alone by utilizing the features of strongly correlated electron systems. High-temperature superconductivity is another phenomenon that occurs in strongly correlated electron systems. Electronic engineering still has infinite potential.

“The electron state in strongly correlated electron systems can be described as a solid produced by electrons. The electron state is like a dilute gas in semiconductors or a liquid in metals. Just as a liquid flows when the container is inclined, electricity flows when a voltage is applied to a metal. In a strongly correlated electron system, where the electron state is ‘solid’, electrons are unable to move because of mutual electrical repellence due to their dense packing. Even when a voltage is applied, no electricity flows. Hence, a strongly correlated electron system is an insulator, or specifically, a Mott insulator. When a minor stimulus such as heat, light or an electric field is applied from outside, a phase change from solid to liquid occurs instantaneously, allowing the electrons to move. In strongly correlated electron systems, this state can be changed at ultra-high speed on a nanometer scale."

A bridge across electron functions

"In a strongly correlated electron system, cross-correlation is possible," continues Tokura. "When a voltage is applied, an electric current flows. When a magnetic field is applied, the system becomes magnetized. These are the usual responses. By bridging different functions of the electron, unusual responses are induced. We call this phenomenon 'cross-correlation'."

A typical example of cross-correlation (Fig. 1) is the 'colossal' magnetoresistance effect, which was achieved with manganese oxide by Tokura in the 1990s. In this phenomenon, electric resistance decreases dramatically by a factor of one-thousand when a magnetic field is applied. This unusual response—a change in electrical resistance when a magnetic field is applied—is an example of cross-correlation. By utilizing a strongly correlated electron system, it is possible to produce a state in which an insulator lacking magnetization and a metal having magnetization compete with each other (Fig. 2). Cross-correlation allows two different functions of the electron to compete in a pair-like manner. When a magnetic field is applied to an insulator, it becomes magnetized and metallic, resulting in a dramatic drop in electric resistance.

Low-energy information processing

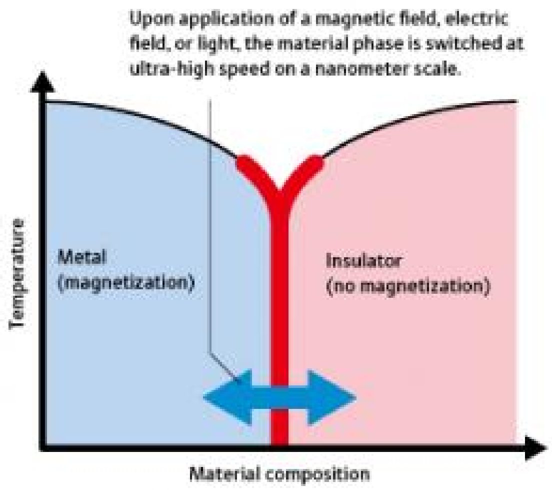

Figure 2: The principle of 'colossal' magnetoresistance. A state is created in which an insulator lacking magnetization and a metal with magnetization compete in a pair-like manner. When a magnetic field is applied to the insulator, it becomes magnetized and turns metallic, resulting in a dramatic decrease in electrical resistance. This rapid phase change can also be achieved by exposure to light or application of an electric field.

In 2007, Tokura established his own research group, the Cross-Correlated Materials Research Group, at RIKEN, and has since been conducting research on Innovation 4. "We aim to develop electronic technologies based on new principles for processing and recording information without conducting electrons."

Existing semiconductor devices process information by conducting electrons. However, this involves the use of electrical power, and energy is wasted in the form of waste heat generated due to electric resistance. The same applies to information recording. In hard disks, for example, an electric current is passed through a coil to generate a magnetic field to reverse the orientation of magnetization in a storage bit during information recording. This also requires a electrical power, generating waste heat and wasting energy, and in large computers, the waste heat generated must be cooled using air-conditioners, consuming additional electrical power.

“If cross correlation, that is, the unusual inversion of magnetization using an electric field, rather than the inversion of magnetization using a magnetic field, could be achieved, it will be possible to record information without wasting energy and with minimal power consumption. We are working on using multiferroics to achieve this.”

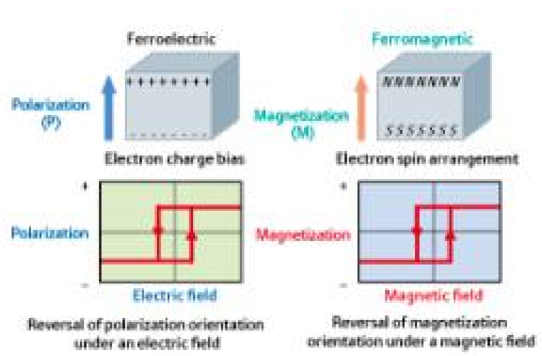

Figure 3: Ferroelectrics and ferromagnetics. Ferroelectrics and ferromagnetics permit the orientations of electrical polarization and magnetization to be reversed by applying an electric field and magnetic field, respectively.

Multiferroics exhibit both ferroelectricity and ferromagnetism. A ferroelectric (Fig. 3) exhibits polarization, with one end positively charged and the other end negatively charged, even in the absence of an external electric field. When an electric field is applied to a ferroelectric, the two poles (+ and –) reverse themselves, allowing information to be rewritten. This phenomenon is used in some prepaid ‘e-money’ card systems for transport and shopping. A ferromagnetic, on the other hand, exhibits magnetization in the absence of a magnetic field, and the orientation of magnetization can be reversed by applying a magnetic field. Ferromagnetics are utilized in hard disks and other data recording devices. “In multiferroics, it is possible to realize the unusual response of reversing magnetization and simultaneously reversing the electrical polarization using an electric field by linking the orientations of electrical polarization and magnetization.”

Polarization is caused by a bias in the distribution of electrons in a material, whereas magnetization occurs when electron spins line up, which otherwise can have either upward or downward orientations, become aligned in a given orientation. Electron spin thus serves as the origin of magnetization.

“The orientation of polarization can be reversed by deforming the orbital in which the electron is accommodated. By utilizing a strongly correlated electron system of multiferroics, the orientation of electron spins can be reversed by deforming the orbital or electron cloud, which would make it possible to link the polarization and magnetization.”

In 2009, Tokura and his colleagues succeeded in experimentally changing the orientation of magnetization at temperatures below –271 °C using an electric field. “If we can improve on this and simultaneously reverse the orientations of magnetization and polarization at room temperature using an electric field, then we will be able to create large-capacity memory that consumes almost no electrical power.”

More recently in June 2010, Tokura’s research group became the first in the world to directly observe skyrmion crystallization, the phenomenon by which electron spin vortices are regularly arranged like a crystal. The result attracted worldwide attention. “It is thought that these electron spin vortices can be moved with a small amount of electric current. Hence, by merely changing the orientation of electron spins one after another, it is possible to move the electron spin vertexes to achieve information processing. This has potential for information processing with minimal power consumption."

New principles for highly efficient solar cells

"We also have an idea for dramatically improving the power efficiency of solar cells," says Tokura. In conventional solar cells, a medium such as a semiconductor absorbs photons and generates a free pair of negative and positive charges. By separating the negative electron and positive 'hole' and transporting them to opposite electrodes, a voltage can be produced. The light-to-electricity conversion efficiencies of modern solar cells is just over 10%, but it should be possible to improve on this efficiency. "Solar radiation contains a broad range of wavelengths. Semiconductor solar cells actually achieve nearly 100% conversion efficiency at particular wavelengths of light, because electron–hole pair can be produced from a single photon at a particular wavelength in each semiconductor with nearly 100% probability. However, an electron–hole pair is also produced when a photon with a shorter wavelength and higher energy level is absorbed, in which case the excess energy is wasted as heat. This accounts for the low power efficiency. If we use a strongly correlated electron system, the wasted energy could be used to create a metallic state and produce a large number of electrons and holes by another mechanism, which could dramatically improve conversion efficiency. Strongly correlated electron systems are being actively studied worldwide, but Tokura and his colleagues are the only group researching their use in highly efficient solar cells.

Basic science will build a bright future

"Physics will continue to yield major revolutions in human society. In recent years, however, it has become increasingly difficult for a single scientist to make a breakthrough alone."

The Japanese government this year established the Quantum Science on Strong Correlation project with the support of the Funding Program for World-Leading Innovative R&D on Science and Technology. RIKEN is responsible for providing research support, and Tokura serves as key investigator. For this project, he has established a dedicated research group, the Correlated Electron Research Group. “This project aims to set groundbreaking principles for realizing Innovation 4 through integrated joint research among outstanding researchers in a broad range of fields, including physics theory, thin-film growth, structural analysis and instrumentation measurement technology. However, if someone ordered me to produce results that could be used in practical applications within several years, I would struggle. Faraday, when asked about why his discovery of electromagnetic induction was so important, answered, ”Who can predict what a newborn baby will become?” The usefulness of the results of basic research like ours is sometimes unpredictable. In the long term, 50 or 100 years, however, they have the potential to produce major revolutions and contribute greatly to future society.”

Provided by RIKEN

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