

# Control magnets by electricity!

## Multiferroics Research



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"TOKURA Spin Superstructure Project" Research Director (2001-2006)

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"TOKURA Multiferroics Project" Research Director (2006-2011)

### Like magnets brought about the use of electricity, they having the potential to totally change the life of mankind

One day, while a shepherd named Magnes was herding his sheep, the iron tip of his staff and the nails in his sandals suddenly became firmly stuck to a large black rock—. This is a legend accounting for the discovery of magnets recorded about two thousand years ago by Pliny of ancient Rome in his book, Natural History. Mankind became intrigued by the mysterious properties of stone called a magnet, which is magnetism, and began to study it. Before long, magnetism became connected with electricity, which led to the development of 'electromagnetism', as a result of which we came to be able to generate electricity of our own and use it.

Magnetism is now used in hard disks or memories in computers.

Now, materials that have unique properties comparable to those of a magnet, which changed the history of mankind, and thus have the potential of greatly changing our lives have suddenly entered into the spotlight. Professor Yoshinori Tokura is taking the lead in advancing the research of 'multiferroics,' which are not materials found in nature by someone like Magnes, but materials produced by humans for themselves by utilizing the results of electromagnetism.

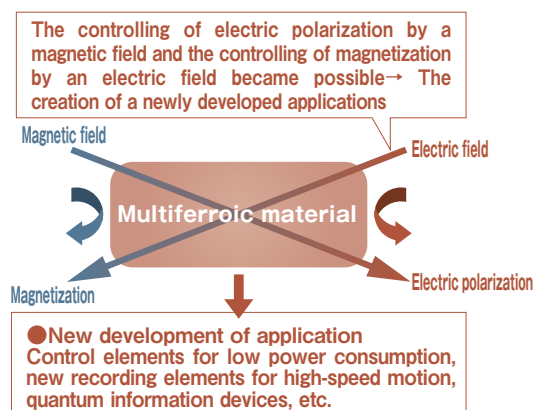
### The practical application had not been achieved more than one hundred years after the "prediction" by Curie

**Multiferroics** are defined as materials that have the two properties of ferromagnetism and ferroelectricity. Electron behavior plays a key role.

An electron rotates itself or spins and thereby exhibits a magnetic property, thus becoming a kind of small magnet, so to speak. However, many of the materials do not exhibit a magnetic property as a whole. Since spin directions of a myriad of electrons in such materials vary, electrons cancel out each other's magnetic property. Still, there is a material in which spin directions are aligned and thereby can exhibit a strong magnetic property as a whole. This is a magnet. Such phenomenon is called magnetization, and the direction of the magnetization of a magnet-like ferromagnetic material can be controlled by applying a magnetic field from outside.

On the other hand, an electron is also negatively charged. However, many of the materials are balanced as a whole, thus not being electrically-charged. Still, some materials are found to be electrically charged; one part is more negatively charged and the other side is more positively charged. This phenomenon is called electric polarization, in which the property called a dielectricity is exhibited, and the direction of electric polarization in a ferroelectric can be controlled by applying an electric field from outside.

#### Conceptual scheme of magnetoelectric effect



Magnetization and electric polarization were understood to be separate phenomena and materials having both ferromagnetism and ferroelectricity had not been identified. However, at the end of the 19th century, Pierre Curie predicted the existence of a material that exhibits a 'magnetoelectric effect,' in which electric polarization occurs when a magnetic

field is applied to it, and when an electric field is applied, magnetization occurs. As predicted, in the 1960s, materials that have both ferromagnetism and ferroelectricity and thus exhibit magnetoelectric effect were discovered, and the remarkably great extraordinary electromagnetic-force effect was named 'multiferroics'. If a great magnetoelectric effect is realized, it becomes theoretically possible to create an efficient and innovative

electric magnet whose magnetic force can be turned on and off by using electricity like when you use a switch, without taking the trouble to wind a coil around an iron core. However, the magnetoelectric effects exhibited by the materials discovered at that time were so weak that time passed without that discovery leading to an application.

## Succeeding in the creation of innovative materials whose <sup>\*1</sup>electric permittivity can be magnified several hundred times when a magnetic field is applied

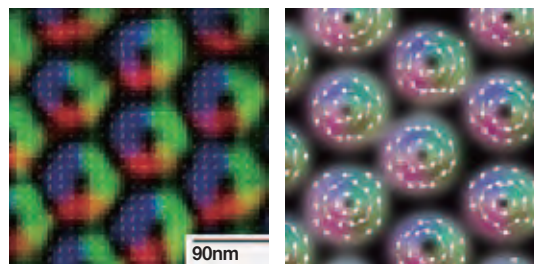
What drastically changed that situation was the ERATO 'TOKURA Spin Superstructure Project,' which started in 2001. With the emergence of high temperature superconducting materials<sup>\*2</sup>, study on 'strongly-correlated electron systems' (the materials in which interactions working between electrons are remarkably strong), which were structural features of such materials, started to be advanced.

It was during that time that Professor Tokura succeeded in theoretically designing the spatial arrangement of electron spin and created a variety of strongly correlated electron systems, including an electronic-type high temperature superconductor.

Professor Tokura engaged in a project aiming to clarify the properties of the strongly correlated electron systems and to develop their manufacturing method, in addition to creating new strongly correlated electron systems. In this project, Professor Tokura also worked on the creation of multiferroics, which had been an unresolved proposition over the years in electromagnetism. Finally, Professor Tokura **succeeded in the creation of materials in which electric permittivity suddenly becomes several hundred times greater by application of magnetic field**. The realization of a significant magnetoelectric effect, which is sufficiently brought into practical use, surprised the world.

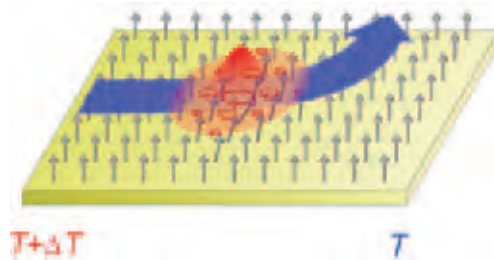
After the ERATO TOKURA multiferroics Project started in 2006, the research proceeded at an accelerated pace. Professor Tokura discovered multiferroics in universal and versatile material systems, such as ferrite and perovskites, and succeeded in their modelization and theorization. Then, he succeeded in the observation and visualization of a skyrmion crystal, which is a helical structure of a spin formed in a material. It is thought that this helical structure produces significant physical interaction in the relationship between electricity and magnetism. Also, Professor Tokura successfully observed

the topological Hall effect resulting from the rotational movement of electrons caused by a huge virtual magnetic field brought about by the skyrmion crystal. In addition, Professor Tokura successfully made an experimental observation of the magnon Hall effect, in which the traveling direction of magnon, which is a spin wave in magnetic material that is represented as particles, curved from the effect of magnetism. Furthermore, **other new discoveries associated with the correlation between electricity and magnetism in solids** were brought about one after another.



Two-dimensional skyrmion crystal obtained by Lorentz electron microscopy (left) and two-dimensional skyrmion crystallogram obtained by Monte Carlo simulation (right)

Conceptual scheme of magnon Hall effect



## Opening of a door leading to the new scientific field of new science quantum science on strong correlation and its application

September 2014, **Professor Yoshinori Tokura was selected as one of the 27 'Thomson Reuters Citation Laureates'**, who are leading researchers selected by the Thomson Reuters Corporation for their achievements based on the data on the number of citations made over the past twenty years. Professor Tokura won his second award following his first Citation Laureates of 2002 in a different category.

The creation of multiferroics is receiving a great deal of attention, which is because their creation has led to the opening of a door leading to quantum science on strong correlation more than simply bringing about the creation of new materials. Like the discovery of magnets that

led to the use of electricity, the great fruitage awaiting us beyond the door will surely change the history of mankind.

This research advanced by the ERATO Project was being promoted by the FIRST Project (Funding Program for World-Leading Innovative R&D on Science and Technology), and now it is promoted for the purpose of contributing to the establishment of a sustainable society through the realization of the ultimate functions of ultra-low power consumption electronics, ultra-low-loss energy transportation, and ultra-high efficiency energy conversion by conducting further research in the future.

\*1 Electric permittivity is a coefficient that shows a relation between an electric charge and the power generated by the electric charge in a material, and each material has its specific coefficient value.

\*2 The material showing the characteristics of superconductivity when the temperature is around 77K (-196°C) or higher than it in the superconductive materials (on page 13).