Press Release

Keio University

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Keio University

Successfully Observing the World's Largest Tunnel Magnetocapacitance of 426%: Prospects for Applications in High-performance Magnetic Sensors and Memory Devices

Researchers have successfully observed the world's largest tunnel magnetocapacitance (TMC) ratio and explained its mechanism. The research team was comprised of Kenta Sato, a second-year master's student at Keio University's Graduate School of Science and Technology, Hideo Kaiju, Associate Professor at Keio University's Faculty of Science and Technology, and colleagues including Hiroaki Sukegawa, Principal Researcher at the National Institute for Materials Science and Gang Xiao, Professor of Physics at Brown University, USA.

TMC is a phenomenon in which capacitance (electrical capacitance, or the amount of electricity that a system can store) changes based on a magnetic field. This phenomenon is observed in textured magnetic tunnel junctions (MTJs) with a thin insulating layer between two magnetic layers. Until now, the largest observed TMC ratio, a figure-of-merit on magnetic sensitivity, has been 332%. In this study, researchers achieved the world's largest TMC ratio of 426% by using an insulation tunneling layer and applying voltage biasing. Furthermore, they explained the mechanism behind this phenomenon using dielectric theory, which incorporates quantum mechanics and statistical theory. These results pave the way for creating new capacitance-detecting, high-performance magnetic sensors and magnetic memory devices.

The research results were published online in *Scientific Reports* (via Springer Nature Group) on May 16 (BST).

1. Main Points of Research

・Successfully observed the world's largest TMC ratio by devising a new type of insulating layer and applying voltage.
・Explained the mechanism behind this success using dielectric theory, an approach which incorporates quantum mechanics and statistical theory.
・Opened up new avenues for the development of high-performance magnetic sensors and memory devices.

2. Background of Research

The field of spintronics has attracted much attention in recent years. It utilizes two properties of electrons, "charge" (electrical charge) and "spin" (the rotation of electrons). Experts speculate that spintronics will be involved in next-generation electronics. Within the field of spintronics, researchers from around the world have focused their attention on studying magnetic tunnel junctions (MTJs), which are created by sandwiching a thin layer of insulation between two magnetic layers. This interest in MTJs is due to their ability to produce large tunnel magnetocapacitance (TMC) ratios at room temperature. TMC is a phenomenon in which capacitance (electrical capacitance, or the amount of electricity that a system can store) changes in a magnetic field. This rate of change in capacitance is referred to as the TMC ratio. The maximum value observed to date has been 332% (see relevant article in references below).

3. Content of Research and Results

In this study, aiming to exceed this record 332% TMC ratio, the research group focused their attention on the insulation layer and the device's voltage. In magnetic tunnel junctions (MTJs), resistance is another factor that changes with a magnetic field. Experts have been well aware of this phenomenon, referred to as "tunnel magnetoresistance (TMR)," for some time. It is even used in modern technology, implemented in the magnetic heads of hard disk drives (HDDs) in computers. As the TMR ratio increases, areal densities of a magnetic recording medium of HDDs are significantly increased. The TMR ratio, however, decreases when "voltage" is applied to MTJs. Conversely, the tunnel magnetocapacitance (TMC) ratio increases when voltage is applied. This is due to capacitance (the electrical storage ability of a system) generated from the spin of electrons at the interface between the magnetic and insulating layers. By utilizing this electrical effect, this same research group achieved a TMC ratio of 332% last year. In this study, the group further focused on the interface structure between the magnetic and insulating layers. In previous studies involving MTJs where an exceptionally large TMC was observed, iron-cobalt (FeCo) and magnesium oxide (MgO) were used for the magnetic and insulating layers, respectively. However, iron-cobalt and magnesium oxide display slight differences in their crystal sizes. To remedy this, the researchers in this study turned to spinel ($MgAl_2O_4$), an oxide of magnesium and aluminum. This is because there is a less than 1% difference in crystal lattice size between spinel and iron. Due to this small difference, the atoms were able to align almost perfectly at the interface between the magnetic and insulating layers, leading researchers to anticipate improvements in the TMC ratio.

Working under this hypothesis, the group fabricated an ultra-high quality MTJ with a thin spinel insulator film sandwiched between two iron magnetic films by using high vacuum magnetron sputtering[1] (Figure 1). The junction was then placed in a magnetic field to investigate the capacitance dynamics. Researchers observed the resulting TMC ratio, which reached up to 426% in this MTJ when voltage was applied (Figure 2). These results are well above the previously observed record of 332%. Furthermore, in addition to the experimental results, subsequent theoretical investigation revealed that a new calculation method incorporating quantum mechanics and statistical theory into dielectric theory[2] can account for the results researchers observed (Figure 3). Theoretical calculations also showed that the TMC ratio could exceed 1000% if magnetic materials with larger spin polarization rates are used.

4. Future Developments

The results of this research are expected to create opportunities for the development of high-performance magnetic sensors and memory devices. They are also expected to be applied in next-generation Internet of Things (IoT) technology—a major driver of the Digital Age—and to make significant contributions to the acquisition, accumulation, and analysis of big data. In the future, these findings are expected to be put to practical use not only in the Information Technology/Information and Communication Technology (IT/ICT) field, but also in a wide range of other fields including environmental energy, healthcare, health sciences, transportation, agriculture, and manufacturing.

5. Acknowledgments

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References

Article detailing the previous largest observed TMC ratio of 332%:
K. Ogata, Y. Nakayama, G. Xiao, and H. Kaiju:
"Observation and theoretical calculations of voltage-induced large magnetocapacitance beyond 330% in MgO-based magnetic tunnel junctions", Scientific Reports **11**, 13807 (2021)

Details of Journal Article

Title of article: Large magnetocapacitance beyond 420% in epitaxial magnetic tunnel junctions with an $MgAl_2O_4$ barrier
Authors: Kenta Sato[1], Hiroaki Sukegawa[2], Kentaro Ogata[1], Gang Xiao[3], and Hideo Kaiju[1, 4] ([1]Keio University, Faculty of Science and Technology, Department of Applied Physics and Physico-Informatics; [2]National Institute for Materials Science; [3]Brown University, Department of Physics; [4]Keio University Spintronics Research Center)
Journal: published in *Scientific Reports* (an open access journal published by Sprinder Nature Group)
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DOI: 10.1038/s41586-021-03832-5

Glossary and References

[1]Magnetron sputtering

A technique that forms a thin film by bombarding inert gas (e.g., argon gas) with a material in an ultrahigh vacuum to eject (or "sputter") the material on a substrate. It is called magnetron sputtering because a magnet is used to increase the frequency with which the inert gas atoms collide with the material.

[2]Dielectric theory

This theory is used to calculate the dynamic dielectric constant, and the model is called the Debye-Fröhlich model. In this study, researchers developed a new theory that combines the Debye-Fröhlich model with the Zhang-Sigmoid theory, the parabolic barrier approximation, and the spin-dependent drift-diffusion model. The conducted experiments from this study lined up well with the predicted results of this new theory.

Figures

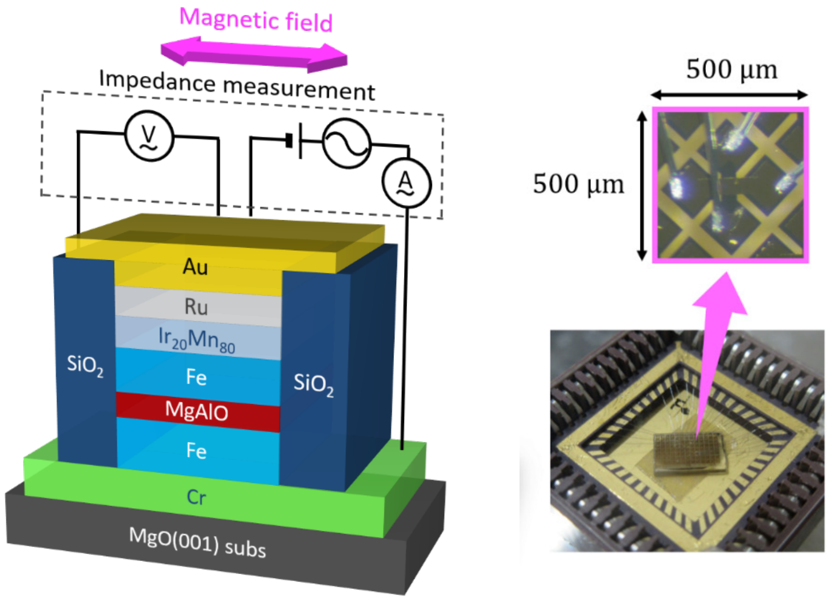

Figure 1. Magnetic tunnel junction (left: measurement setup, right: photograph of prototype)

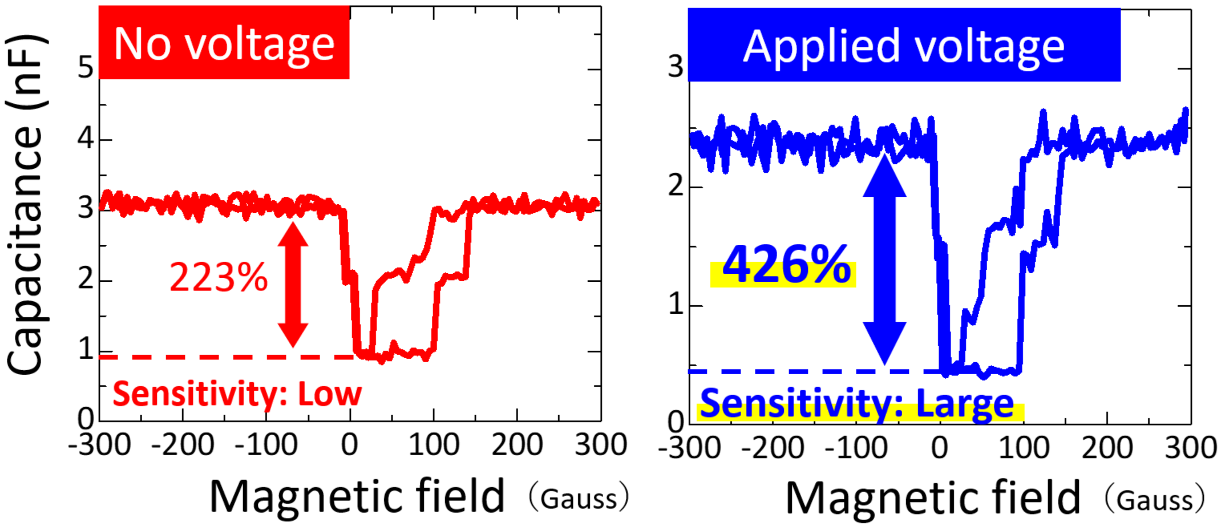

Figure 2. 426% capacitance ratio achieved once voltage was applied

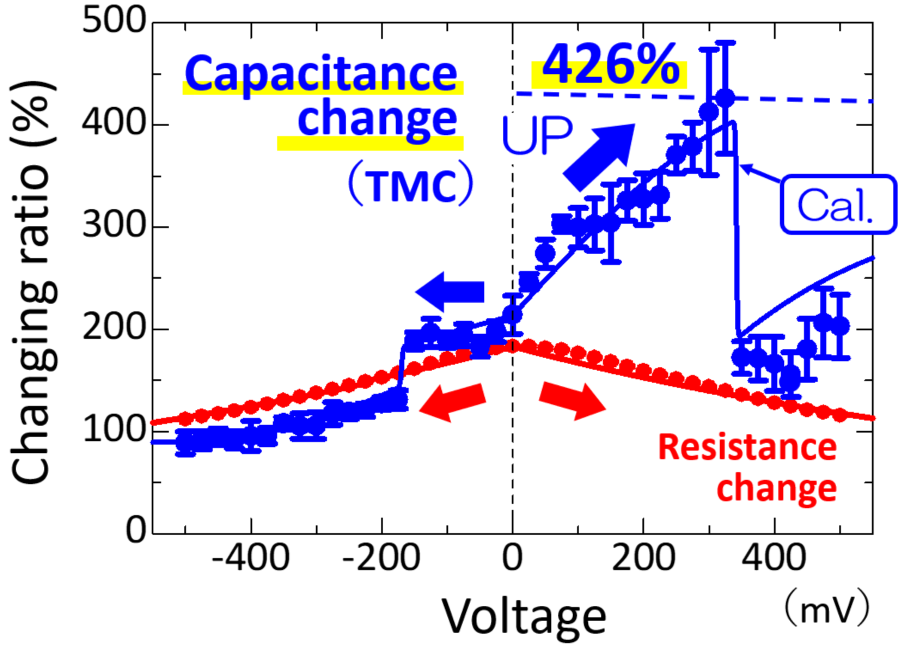

Figure 3. Comparison of experimental and calculated results
(The blue circles are the results of the TMC experiment. The blue line are the calculated results.
The red circles are the results of the TMR experiment. The red line are the calculated results.)

*Please direct any requests or inquiries on press coverage to the contact information provided below in advance.

Inquiries about research
Associate Professor Hideo Kaiju,Department of Applied Physics and Physico-Informatics,
Faculty of Science and Technology, Keio University
TEL: +81 (0)45-566-1428
Email: kaiju@appi.keio.ac.jp

Inquiries about press release
Keio University Office of Communications and Public Relations (Contact: Sawano)
TEL: +81 (0)3-5427-1541
FAX: +81 (0)3-5441-7640
Email: m-pr@adst.keio.ac.jp
https://www.keio.ac.jp/en/