Spintronics introduction for KOSEN students: Quantum mechanics and ultimate electronics

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－ Quantum mechanics and ultimate electronics －

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1. Spintronics

When I say, “I study spintronics” to someone, they often ask, “What is spin?” After I provide a brief explanation about spin, they sometimes act like they were allergic, and say, “It is too difficult for me to understand.” But wait a minute. I think there are few people who truly understand quantum mechanics. Even Einstein was initially skeptical about quantum mechanics, hence ordinary people are not likely to grasp it instinctually. However, quantum mechanics seems to hold true. We have no choice but to accept it. Since the age of quantum computers is expected to be realized following the introduction of supercomputers, I feel daily that it is impossible for us to escape quantum mechanics even if we wanted to. In that case, I think it is better to try hard to contribute to the development of quantum mechanics, even if many of us do not understand it yet.

If I was asked, “What is a quantum?,” I would answer, “It is a non-contiguous value.” Scientifically speaking, it is a “discrete value.” Classical mechanics, which was discovered by legendary physicist Newton, is based on “analog physics,” which continuously captures the motion of an object. By contrast, I define quantum mechanics, which was found by Schrödinger, Bohr and Pauli, relatively recent legendary physicists, as “digital physics,” which takes discrete values. The truth of quantum mechanics is that the value can only be known probabilistically. The position of electrons cannot be defined unless we see them. Even Einstein could not understand this incomprehensible explanation at first, and he denied quantum mechanics with the words, “God does not roll the dice,” and “Is the moon not present when I am not looking?” However, since Pauli received the Nobel Prize by the recommendation of Einstein, it seems that Einstein had gradually accepted quantum mechanics.[1, 2]

The reason why the study of spintronics appeared is that, as shown in Fig. 1, electrons essentially have four physical quantities: 1. charge, 2. mass, 3. spin angular momentum, and 4. magnetic moment. These quantities can be classified by their abilities into two properties: charge (property to pass an electric current) and spin (property to become a magnet). The word “electronics” derives from “electrons”; however, many people might think of “semiconductor engineering” when they hear the word “electronics.” Semiconductor engineering considers only 1.

charge and 2. mass, while basically ignoring 3. spin angular momentum and 4. magnetic moment. This is because semiconductor engineering was created by considering "electromagnetism" as "true." Faraday and Maxwell, who created electromagnetism, may have known about the existence of 3. spin angular momentum and 4. magnetic moment. However, it is conceivable that they did not include spin because they created the rule of electromagnetism based on the "meter." When studying spintronics, people come across the keywords "spin current" and "spin diffusion length]".[3] Spin current is the beneficial feature of spintronics, and it results in disappearance to the human eye when the up-spin and the down-spin become even and relaxed at the distance called the "spin diffusion length." The spin device, therefore, can be effectively used only within the spin diffusion length. When Maxwell created "Maxwell's equations" that cover electromagnetism, he may have overlooked the existence of spins, as they are quite small and disappear in the order of nanometers or micrometers at most.[4] In semiconductor engineering based on electromagnetism, Moore's Law had the strongest impact among various developments. The law indicated that the technology for performing ultra-fine processing is the most important, and the processing power of the CPU increases as the transistor becomes smaller to increase the work power of the semiconductor device, and it lasted for more than 50 years. However, as anyone may know, a transistor cannot be made smaller than an atom. Moore's Law had its limit, and Moore himself finally declared the end.

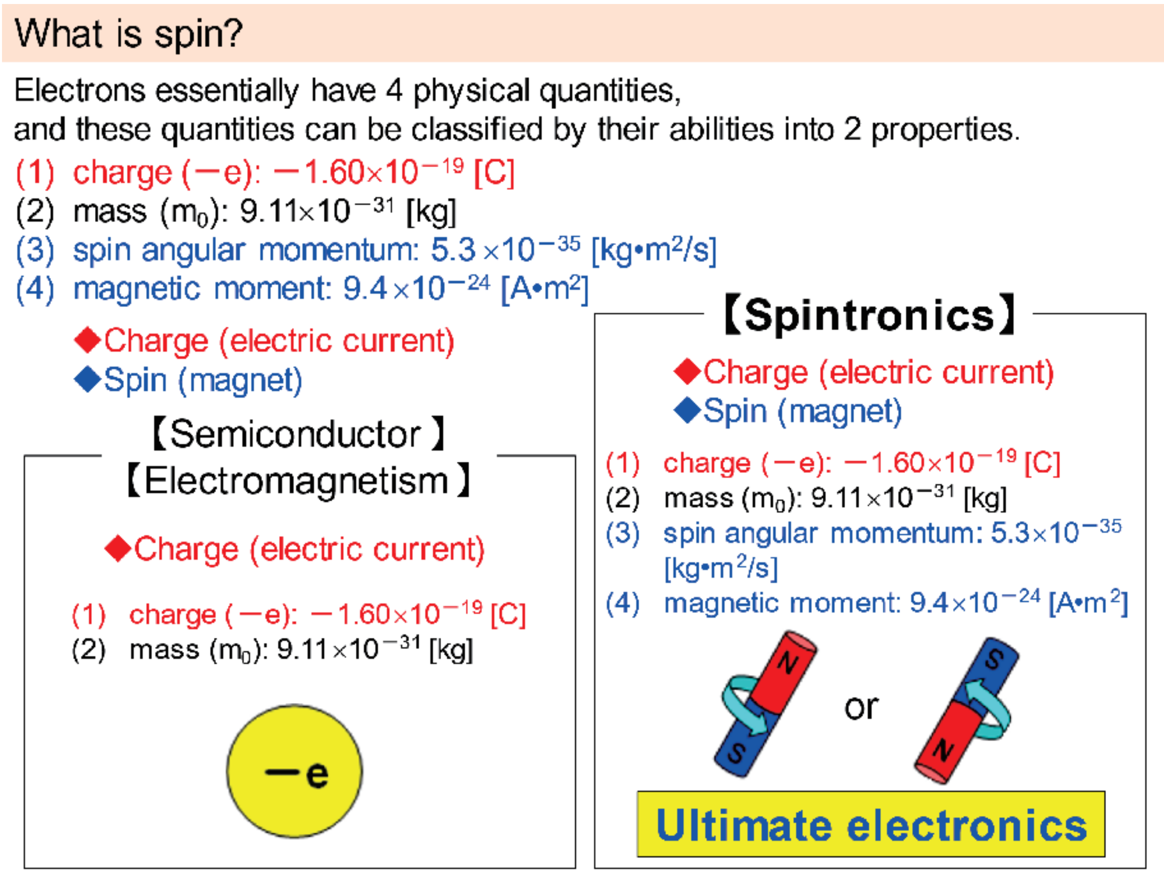

Fig. 1 What is spin?

What, then, should researchers do now? There is a phrase, ‘Beyond CMOS (More than Moore),’ which approaches the development of electronic devices by exceeding the existing CMOS transistor that uses silicon semiconductors. Semiconductor researchers are trying to break Moore’s Law with, for example, “high dielectric constant gate insulating film” (high–k) and “semiconductor Ge.” Meanwhile, some researchers consider going back to the origin of electronics. As you carefully look back what was mentioned above, you will find that electrons essentially have two types of properties, charge (the property of passing an electric current) and spin (the property of becoming a magnet); but semiconductor engineering basically considers only charge (the property of passing current). Shouldn’t we be more suspicious about not effectively using spin (the property of becoming a magnet)? The “spin current due to electron spin angular momentum” should be flowing inside the existing electronic device that has undergone ultrafine processing on the nanometer scale, in the same way as the “current due to electron charge.” The number of bits can be increased by effectively using the spin current, since spintronics considers electrons to have two types of balls, clockwise and anti-clockwise, while electrons in semiconductor engineering have one type of ball. Furthermore, the classical mechanical rotation is most stable in the non-moving state (resting state), as the ball eventually stops moving after it has been placed on the ground. By contrast, the electron spin, which is the quantum mechanical spin, is most stable in permanent motion (a state of continuous rotation such as that of the earth) in terms of condensed matter physics. Therefore, the idea is to effectively utilize the energy.

To summarize briefly, one of the basic principles of spintronics suggests that you consider all the physical properties of electrons to continuously develop the existing electronic devices made by nanometer-scale ultra-fine processing technology.[5]

2. Magnetization Reversal

In the field of spintronics, the most basic and important physical phenomenon is “magnetization reversal.” In brief, the electrical resistance is high when the magnets are aligned in opposite directions, and the electrical resistance is low when the magnets are aligned in the same direction, as shown in Fig. 2. Since switching occurs even in the same element, it is called magnetization reversal. In technical terms, it is called “spin-dependent scattering,” because it is the difference of electrical conductivity depending on the direction of electron magnetization.

The famous effect using this magnetization reversal is the giant magnetoresistive effect (GMR effect), which was awarded the 2007 Nobel Prize in Physics for its contribution to the development of magnetic heads of hard disk drives (HDD).[6, 7] In addition, the discovery of the tunnel magnetoresistive effect (TMR effect) and the improvement of crystallinity caused a breakthrough, and the TMR elements are now used in the magnetic heads of HDDs.[8, 9, 10, 11, 12, 13]

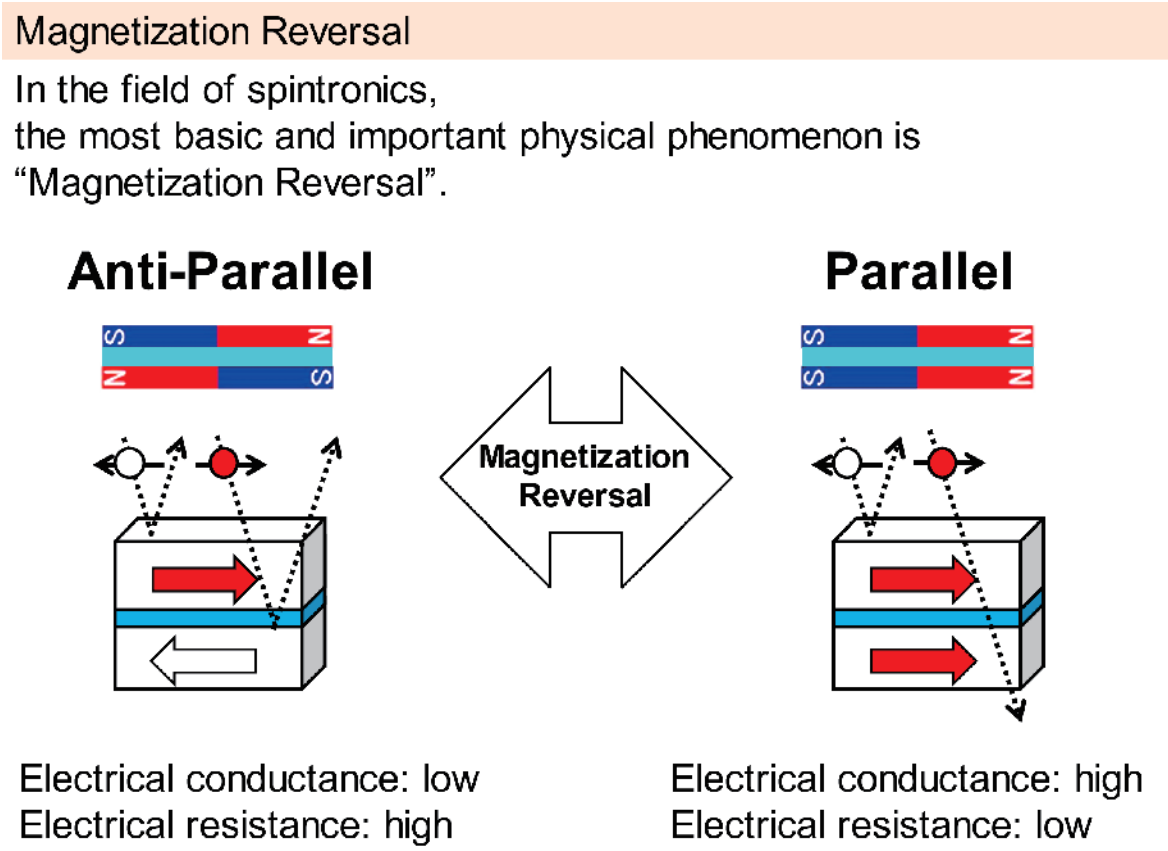

Fig. 2 Magnetization reversal

3. Conclusion

As indicated by the title "Spintronics introduction for KOSEN students," this paper is not for spin experts. There are several reasons why I decided to submit this paper, but the primary one is to write a paper that would be useful when teaching graduation research for fifth-year students of KOSEN, and when providing orientation to students in an advanced course, including those from other departments.[14] In addition, since the collaborative education program between Interdisciplinary Graduate School of Engineering Sciences at Kyushu University and nine colleges of technology located in Kyushu and Okinawa districts will officially start in 2023, I think this paper will be useful when cooperating and starting collaborative research with teachers and students from other laboratories. Since "inheritance and development of knowledge" is the mission of an institution of higher education, I would like to carry out "inheritance of knowledge" for KOSEN students by posting this paper on a regular basis, and achieve the "development of knowledge" by utilizing the posting in my daily research activities.

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