Spin will change our lives: electronics based on new principle

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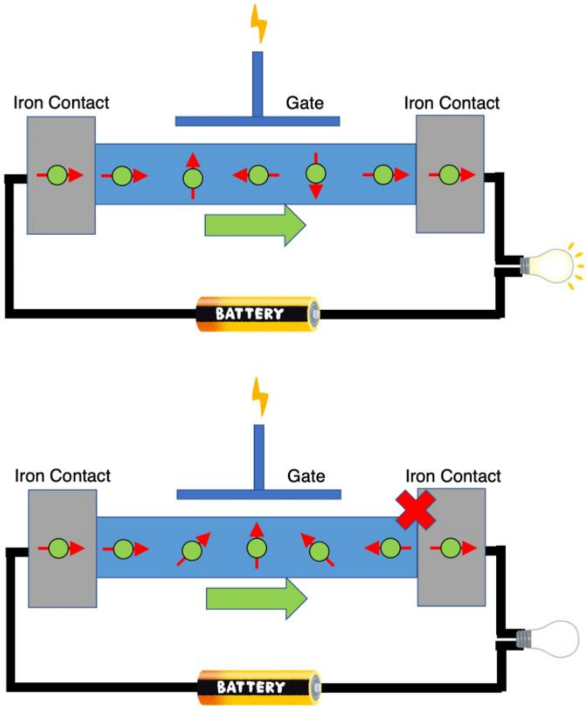

There are billions of transistors in a smartphone. These transistors control the amount of electric current flowing in electric circuit. The performance of electronic devices has been dramatically improved by miniaturization. The number of transistors on a microchip continues to rise as transistors become smaller. Moore's law suggests that the number of transistors on a microchip doubles approximately every two years, while the cost of manufacturing these chips decreases. It has been said that electronics technology grows exponentially according to Moore's law, but in reality, there is a limit to the growth of technology because of the limit to the miniaturization of transistors.

Because of these limitations in the development of electronics, there is a need to develop new devices based on new principles. This gave rise to the field of spintronics, which utilizes the spin of electrons. Spintronics aims to exploit the spin of electrons to develop novel electronic devices that have unique advantages over traditional electronics.

The spin of a particle is property like how an object can spin on its axis. In fact, the spin of a particle is not a physical rotation in the traditional sense, but rather a fundamental quantum mechanical property. However, the important thing is that the spin is a fundamental property that affects how particles interact with magnetic fields. Many particles, such as electrons and atoms, have spin, and spin is strongly related to the magnetism of a material.

The spin field-effect transistor (SFET) was conceived by Datta and Das in 1989. The role of a transistor is to control the amount of electric current flowing in a semiconductor between two electrodes by applying a third electrode named "gate", and SFETs use the spin property of electrons to achieve this.

Consider a semiconductor sandwiched between two iron contacts to pass a current through the semiconductor. Due to the magnetic properties of iron, the direction of the electron spins in the iron contacts is oriented in a certain direction. When a voltage is applied to two iron contacts, electrons go from one contact into the semiconductor and from the semiconductor into the other contact. When electrons enter the iron contact from the semiconductor, current flows easily if the direction of the electron spin is consistent with the direction determined at the iron contact.

Then consider controlling the current by controlling spin orientation using a third electrode (gate). The electron flowing through a semiconductor rotates its spin direction due to spin-orbit interaction. Spin-orbit interaction is a property of semiconductors and acts as an effective magnetic field to rotate the spin direction. The magnitude of the spin-orbit interaction can be modulated by the voltage applied to the gate attached to the semiconductor. As a result, the rotation of spin orientation can be controlled, and current flows well when the spin orientation rotates exactly 360 degrees while the electrons move through the semiconductor. Conversely, current flow is difficult when the spin direction is rotated 180 degrees while the electrons move through the semiconductor.

Therefore, the current can be controlled by controlling the rotation of spin direction with the third electrode.

One of the key advantages of spintronic devices is the potential for low-power consumption. Spin-based devices can operate with less energy because they rely on manipulating the spin state rather than the movement of charge, which reduces heat dissipation and enables greater energy efficiency.

In electronics, devices have been developed to take advantage of the transistor's ability to control current at a third electrode; SFETs are important devices for spintronics because they achieve the same function by working on the spin of an electron. Spin is essentially related to magnetic properties, and it has been the usual practice to control spin by means of a magnetic field. However, the use of semiconductors with spin-orbit interaction in SFETs makes it possible to control spin by means of an electric field. Specifically, by applying a voltage to the gate electrode, the spin-orbit interaction, which acts as an effective magnetic field for the spins, can be modulated. Compared to control using a magnetic field, control of spins by an electric field has the advantage of being able to drive spins locally and at very high speeds, as well as having low power consumption.

SFETs can also be used to read out the spin orientation of iron electrodes at high speed, and are expected to be used as memory. This memory is a type of memory called non-volatile memory, which can retain stored data even when power is removed. Nonvolatile memory is commonly used in various electronic devices, including computers, smartphones, digital cameras, and portable media players. Replacing non-volatile memory in various devices with spintronic devices such as SFETs can provide fast access times, and low power consumption.

Spintronics may renew smartphones, PCs, and renew our lives. To this end, research is being conducted both in understanding the nature of spin in fundamental physics and in its application to devices. Might you be the one who helps makes this technology something everyone uses every day?

I wrote sentences in Japanese, translated them into English using DeepL, and then revised the sentences myself.

I thank Tomoaki Okochi and Prof. Mark Vagins for reviewing my draft. Their reviews helped me to improve this essay.

Reference

[1] Supriyo Datta, Biswajit Das; Electronic analog of the electro-optic modulator. Appl. Phys. Lett. 12 February 1990; 56 (7): 665–667. https://doi.org/10.1063/1.102730

[2] Junsaku Nitta. 電界効果スピントランジスタの現状と展望. Electrochemistry, 71(3), 180-184, 2003. https://doi.org/10.5796/electrochemistry.71.180