The first spintronic transistor

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For the past 60 years, the electronic device known as the transistor has been fundamental to an exponential growth in technology, especially when harnessed together in the integrated circuit chips that are employed in computers.

To provide the PCs used by millions of people with ever-increasing speed and memory capacity, chips are now manufactured containing over a billion transistors. Each transistor can be as small as only 32 nanometers across, or a width of about 96 silicon atoms (one meter equals a trillion nanometers).

While incredibly tiny, these transistors still make use of the same principles as when they were invented in 1947. Electric currents (which consist of moving negatively charged electrons) are manipulated and detected in materials known as semiconductors. At first germanium was used, but now mainly silicon.

For the first time now, researchers have developed a new type of transistor—running at normal temperatures—that utilises a feature of electrons known as spin, rather than charge.

On December 24, the creation of a so-called spin-field-effect transistor (FET) was announced in *Science* magazine. An international team of scientists took part in the effort, from the Hitachi Cambridge Laboratory in the UK, Texas A&M University, the Universities of Cambridge and Nottingham in the UK, and at Academy of Science and Charles University in the Czech Republic [1].

Such a transistor was proposed theoretically by Supriyo Datta and Biswajit Das in 1989 at Purdue University. It has taken more than 20 years to realise because of the enormous technical difficulties involved in advancing beyond the standard semiconductor approach, a task involving millions of dollars of investment by the electronics industry and dozens of teams of researchers following a variety of different approaches throughout the world [2].

When physicists first elaborated the modern theory of the atom in the 1920s, they realised that the movement of clouds of electrons surrounding the nucleus in atoms could only be understood through quantum mechanics. To explain the properties of atoms, electrons must not only have a charge and a mass, but a new property called spin, which is closely related to magnetism. Unlike the spin of a football, for example, the spin of an electron in a magnetic field has only two possible directions—usually chosen to be “up” and “down.”

The application of electron spin is called spintronics (short for spin transport electronics) and is now a highly developed branch of engineering [3]. Spintronic devices use a current of electrons where there is more of one type of spin than the other, either up or down. This is known as a spin-polarized current.

Its main application so far has been in memory devices such as the hard drives in a laptop. These rely on electrons passing through metallic ferromagnetic materials in what are called giant magneto-resistance (GMR) devices. If the ferromagnetic material is in the form of thin films, separated by non-magnetic layers, there is a change in electrical resistance to the current passing through, depending on whether the magnetism in the layers is in the same or opposed directions. (The 2007 Nobel Prize in physics was awarded to Albert Fert and Peter Grünberg for the discovery of GMR).

The latest discovery shows that spintronics can also be used in semiconductors as well as metallic magnetic memory devices. Jairo Sinova of Texas A&M explained, “One of the major stumbling blocks was that to manipulate spin, one may also destroy it. It has only recently been realized that one could manipulate it without destroying it by choosing a particular set-up for the device and manipulating the material.”

The team were able to do this, he said, “by exploiting our findings from our study of the spin Hall effect six years ago. It is the combination of these basic physics research projects that has given rise to the first spin-FET.” The spin Hall effect refers to the production of transverse electrical voltages in the device, which are used as the output signal and depend on the orientation of the electron spin in the transistor.

Dr. Jörg Wunderlich of the Hitachi laboratory, senior researcher in the team, pointed to the limitations being reached in using smaller and smaller transistors in computers. To overcome these limits, new physical principles of operation would be needed, such as using “spin” instead of charge.

Wunderlich admitted that whether spin-based devices will become an alternative to the standard electron-charge-based transistors in computer chips has yet to be determined. However the team had shifted research from academic speculation to prototype microelectronic device development.

“For spintronics to revolutionize information technology, one needs a further step of creating a spin amplifier,” said Sinova.

The development of cheaper, faster and smaller microchips is known to all students of computing as Moore's law, which postulates that the power of chips would double every two years. From the 1970s when Gordon Moore first made the hypothesis, this has in fact been the case. But in the next few years this process must reach a limit—silicon transistors are likely to give rise to unreliable chips if packed closer than 11 nanometers apart.

One of the most serious issues is keeping arrays of closely packed transistors cool, which has meant that the speed that the transistors switch on and off—the so-called clock rate—has reached a maximum of three to four gigahertz in modern computer chips. To improve performance, microchip designers moved to placing two or more processors, or cores, on the same chip. Supercomputers have already been developed with thousands of cores, but the approach is now being used in personal computers. Each core works at the same speed as a single processor but is linked with the others through parallel processing using specially developed software. It is now common to have quadruple cores as in the Intel i7 and the AMD Phenom chips.

As well as the development of spintronics, the microchip industry is researching a range of options to overcome the current limitations of size and speed [4]. These include the use of new types of materials, especially nanotubes, which are tubes of carbon a few nanometers thick, and graphene, which is carbon in a two-dimensional sheet one atom thick.

Also being studied are optical computers that are based on the movement of photons of light rather than electrons and biological computers that use organic molecules such as DNA or RNA rather than transistors.

A further goal is to use circuits made from individual atoms, electrons or even photons, so that interactions are governed by the laws of quantum mechanics rather than ordinary electronics.

One possible development in spintronics would be to use the spin of individual electrons, rather than in polarized currents. Quantum computers have been investigated theoretically and are understood to be incredibly dense and fast. Their practical realisation is still only in the early stages.

Notes:

1. Spin Hall Effect Transistor , Jörg Wunderlich, et al. , *Science*, Vol. 330, p. 1801 (2010).

2. http://www.sciencedaily.com/releases/2010/12/101223144034.htm

3. Spintronics, *Scientific American*, June 2002.

4. The Next 20 Years of Microchips, *Scientific American*, January 2010.