Towards miniature supercomputers

Spintronics

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Will it continue to be possible to achieve further progress simply by miniaturizing the transistors used in microprocessors and the memory cells in disk devices? Spintronics might hold the key to a new breakthrough in nanotechnology

According to Moore's law, miniaturization has continuously led to an exponential increase in the quantity of information that can be processed, stored and transmitted per unit area of microprocessor, memory, and light fiber, respectively. A modern integrated circuit now contains one billion transistors, each smaller than 100nm (=10^{-7}m) in size, i.e. five hundred times smaller than the diameter of a human hair. The crossing of this symbolic 100nm threshold at the outset of the 21st century ushered in the era of nanotechnology. As the size of transistors decreases, their speed increases and their price falls. Today it is much less expensive to manufacture one transistor than to print a single letter.

Yet will miniaturization alone continue to produce progress? Despite the series of successes that industrial laboratories have scored over the past 40 years in surmounting one technical and physical barrier after another, there is now a prevalent sense that in the near future a qualitative change is now in store for us in terms of the methods of data processing, storing, encoding and transmission. For this reason, governments in many countries are financing ambitious interdisciplinary programs aimed at insuring active participation in the future development of nanotechnology.

A promising direction

Among the many proposals for where to take such research, the field of spintronics, i.e. electronics aimed at understanding electron spin phenomena and at proposing, designing and manufacturing devices to harness these phenomena, is now playing a major role. The hopes placed in spintronics are founded on the well-known fact that since magnetic monopoles do not exist, random magnetic fields are significantly weaker than random electric fields. For these reasons, magnetic memories are non-volatile, while memories based on an accumulated electric charge (dynamic random access memory, or DRAM) require frequent refreshing.

One of the ambitious goals in the spintronics field is to create magnetic random access memory (MRAM), a type of device that would combine the advantages of both magnetic memory and dynamic random access memory (DRAM). This requires novel methods of magnetizing memory cells and reading back the direction of such magnetization that would not involve any mechanical systems. Another important step along this path would be the ability to control magnetization isothermally, by means of light or electric field. Modern devices expend relatively large amounts of energy on controlling magnetization (i.e. storing data), as they employ magnetic fields induced via electric currents.

The development of more "intelligent" magnetization control methods would also make it possible to build spin transistors, devices composed of two layers of ferromagnetic conductors separated by non-magnetic material. It stands to reason that if carriers injected into the non-magnetic layer preserve their spin direction, then the electric conductivity depends on the relative direction of the magnetization vectors in the ferromagnetic layers.

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This could offer a means of producing an energy-conserving and fast switching device, as it would allow current to be controlled without changing the carrier concentration. An obvious prerequisite for such a transistor to operate is the efficient injection of spin-polarized carriers made of ferromagnetic material into the non-magnetic area. Also, there should be no processes that could disrupt the spin polarization. Simultaneously, researchers are seeking ways of genera-ting and detecting spin currents: here, the underlying conviction is that the movement of electrons with opposite spins does not entail any losses, yet can carry information. This would lay the foundations for the development of devices with significantly reduced heat dissipation.

East News

It is now the spin - internal angular momentum - of electrons, rather than their charge, that is opening up new perspectives in modern electronics

Perhaps the most important intellectual challenge to be faced in spintronics is to develop a field of "quantum computer science." Scientists the world over have joined efforts to lay the theoretical foundations for this new discipline, one notable example being the Horodecki family from Gdańsk. Experiments conducted by David Awschalom's group show that spin degrees of freedom are of particular importance as they maintain their phase coherence significantly longer than orbital degrees of freedom do. Electron spin is therefore much more suitable than electron charge for putting into practice modern ideas for performing numerical computations using the superposition of quantum states. Spin nanostructures might consequently alter the basic principles not only in the design of electronic elements, but also in the very computer architecture that has been in use for half a century. It is noteworthy that quantum encoders are already now being sold and installed: such devices use the polarization of light to encode the transmitted information, and the unauthorized interception and reading of this information appears to be impossible.

Ferromagnetic semiconductors

Modern research in the field of spintronics deals with almost all types of materials. Nevertheless, it is commonly believed that the development of spintronics will mainly be molded by ferromagnetic semiconductors, as they combine complementary recourses of semiconductor materials and ferromagnetic metals. Here, the fundamental research problem is to identify the extent to which the methods that have been so successfully applied to controlling the density and degree of spin polarization of carriers in semiconductor structures might be employed to control the magnetization magnitude and direction. Another important issue is to develop methods for injecting spin-polarized carriers into semiconductors. Apart from the possibility of designing the aforementioned magnetoresistive sensors and spin transistors, polarized carrier injection could prove to be useful as a method for the fast modulation of semiconductor lasers and would allow surface-emission lasers to work in unimodal fashion.

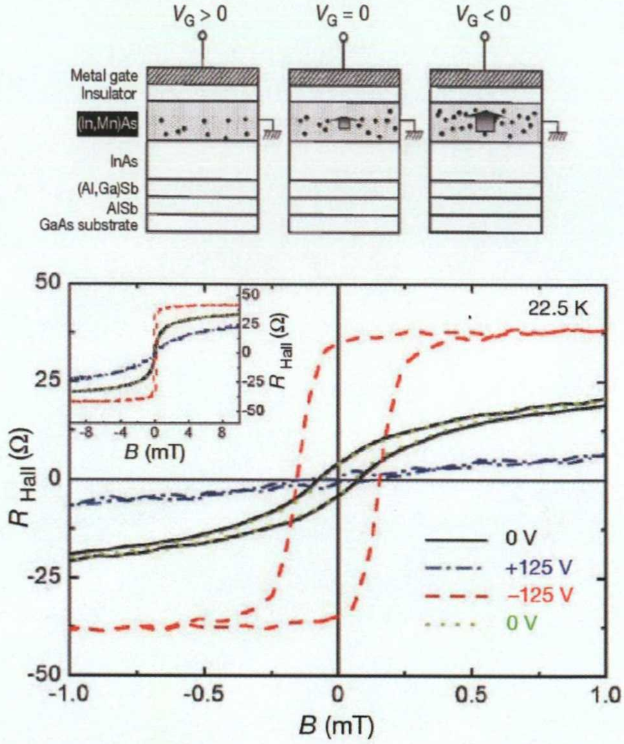
Since semiconductor technology is the most advanced for the III-V and II-VI periodic table group semiconductor compounds, the discovery by Hideo Ohno and collaborators of carrier-induced ferromagnetism in such compounds as $In_{1-x}Mn_xAs$ and $Ga_{1-x}Mn_xAs$ came as a landmark achievement. In these materials, divalent Mn ions provide localized spins and function as acceptor centers that in turn provide holes. In another technologically important group of semiconductors, II-VI compounds containing magnetic ions, the densities of spins and carriers can be altered independently, similarly to the case of IV-VI materials, in which hole-controlled ferromagnetism was discovered by Tomasz Story and Robert R. Gałązka at the Institute of Physics of the Polish Academy of Sciences as early as in the 1980s. Actually, studies of diluted magnetic semiconductors have since the late 1970s been the specialty of the Warsaw semiconductor school established by Leonard Sosnowski, and are now being developed by about a dozen professors, Sosnowski's former students.

Laboratories in Grenoble and Warsaw, led by Yves Merle d'Aubigné and the present author, have joined efforts to undertake comprehensive research dealing with carrier-induced ferromagnetism in II-IV materials containing Mn. Technological and experimental studies conducted with the use of magnetooptical and magnetic methods have led to the discovery of ferromagnetism in a 2-and 3-dimensional systems, confirming theoretical predictions of the present author.

Spin transistors for the future?

Based on experimental results, the present author has proposed a theoretical model of hole-induced ferromagnetism in III-V and II-VI group semiconductors containing Mn. Despite the rather complex physical situation this theoretical model has enabled both the author and Allan H. MacDonald from the University of Texas to describe the termodynamic, micromagnetic, optic and transport properties of a wide range of diluted ferromagnetic semiconductors, as well as to challenge a number of competing theories. It is often argued that owing to these studies $Ga_{1-x}Mn_xAs$ has become one of the best-understood ferromagnets. This material is now used as a testing ground for various numerical methods to derive the properties of disordered magnetic structures from first principles.

With an understanding of the properties of diluted ferromagnetic semiconductors, the present author and associates were able to propose and experimentally prove the existence of many new phenomena that allow for magnetization control using stress, light, current and electric field. These phenomena do not occur in other ferromagnets, and this consequently gives rise to the possibility of constructing as-yet unknown IT devices. The search for new ferromagnetic semiconductors with an above-room-temperature Curie point, as initiated by the theoretical proposals put forth by the present author, is one of the most rapidly developing branches of materials science.



H. Ohno et al., Nature 408, 944 (2000)

Modification of a ferromagnet (In,Mn)As by the electric field - depending on the applied gate voltage the ferromagnetic hysteresis are visible or disappear

The International Technology Roadmap for Semiconductors, an influential advisory body jointly sponsored by all the world leaders in the field of semiconductor electronics, has for years been monitoring and forecasting the technological development in information and communication technologies. In connection with the great progress made in the field of semiconductor spintronics in the past few years, spin transistors were for the first time described in the latest assessment issued by this body, entitled 2004 Update - Emerging Research Devices. Here it was also suggested that spin transistors might replace unipolar silicon transistors, which have been so successfully employed since the 1960s. ■

Further reading

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