Advanced Electronic Devices

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OVERVIEW: The continued march of miniaturization in electronics provides a constant challenge for designing future technologies. For several decades, it has been realized that quantum mechanics plays a significant part in the operation of commercial semiconductor devices. The Hitachi Cambridge Laboratory was established to create new device concepts based on quantum mechanical principles, and conducts this research in collaboration with Hitachi's worldwide network of research laboratories. Such nanoelectronic devices are expected to be the basic building blocks of future microprocessors, memory chips and HDDs.

INTRODUCTION

THERE is a constant demand for faster, higher density and lower power forms of information processing and storage. This inevitably leads to the need to make individual devices such as transistors, memory nodes and hard disk read-heads smaller and smaller. These challenges are being met by Hitachi's long-range research laboratories in Japan, the USA and Europe.

The Hitachi Cambridge Laboratory (HCL) was established in 1989 and physically located within the Cavendish Laboratory, University of Cambridge, U.K. with the aim of creating new concepts of advanced electronic and optoelectronic devices. In close collaboration with the Microelectronics Research Centre (MRC) of the University, HCL is a truly international team of researchers, and its open research environment has produced a profitable collaboration for over a decade and a half. HCL specialises in advanced measurement and characterisation techniques, and MRC specialises in nanofabrication. HCL works in close collaboration with the Hitachi San Jose Research Center in the USA, and the Hitachi Advanced Research Laboratory in Japan to produce devices which will keep Hitachi in the lead of electronic information processing into the future.

The main research subject is nanostructure physics for future electronic and optical devices, including nanospintronics, quantum information processing, single-electron devices, nanoelectronics and organic nanoelectronics. In this article we will describe three projects illustrating the work that is done in HCL.

NANOSPINTRONICS

A technology has emerged called spintronics, where it is not the electron charge but the electron spin (magnetic field) that carries information. This offers opportunities for a new generation of devices combining standard microelectronics with spin-dependent effects.

Hitachi is one of the largest manufacturers of hard disk devices for information storage. HCL is part of a global collaboration within Hitachi, aimed at developing new spintronic devices for future hard disk and memory applications.

Projects under investigation include the study of fundamental spintronic physics, and the production of devices more specifically aimed at making new read-head sensors and novel methods of magnetic storage.

Spin Hall Effect

This phenomenon, obtained with a novel and unique design of optoelectronic device, adds a new spin to the possibility of electronic circuits with low energy consumption. The team is formed by physicists from the HCL, the Institute of Physics of the Academy of Sciences of the Czech Republic, the University of Nottingham, U.K., and Texas A&M University, USA.

The normal Hall effect manifests itself as a voltage perpendicular to an electric current flowing through a conductor in a magnetic field. The magnetic field deflects the moving charges to the sides of the conductor, resulting in the Hall voltage, which is used to measure magnetic fields.

A different phenomenon, the spin-hall effect, was first predicted in 1971. Here, the moving electrons, which carry with them a tiny magnet called the spin, collide with impurities and deflect to the right or the left depending on the orientation of their spin, leading to magnetisation even without a magnetic field (see Fig. 1) .

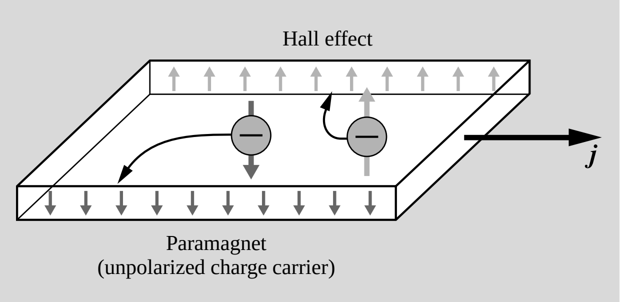

Fig. 1—The Spin Hall Effect.
Local magnetization is created with an electric current.

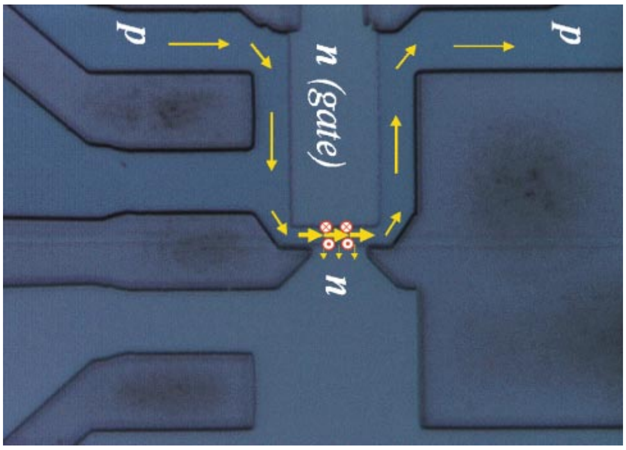

Fig. 2—Device Used to Demonstrate the Spin Hall Effect for First Time.
The lateral p-n junction device made of gallium arsenide which was used to demonstrate the spin Hall effect for the first time.

Despite its intriguing ramifications, and probably because of the perceived difficulty in observing the effect, the theory disappeared into virtual obscurity until 1999, when it was rediscovered and further elaborated. Four years later, experimental efforts to observe it took on a renewed energy when two independent teams proposed a novel effect called the intrinsic "Spin-Hall Effect." This predicted a similar magnetisation but without the need for collisions.

This prediction touched off a theoretical firestorm, resulting in more than 50 articles arguing for and against the possibility. Meanwhile, as the theoretical debate raged on, the team developed a new type of optical device which measures the magnetisation at each side of a semiconductor chip using built-in light emitting diodes and in which the active region is formed by a clean thin semiconductor layer to minimise collisions. The development of this special device led to the breakthrough (see Fig. 2).

This novel device was used to observe the intrinsic effect experimentally for the first time. The detected magnetisation is more than 10 times larger than that seen in the non-intrinsic effect in conventional bulk semiconductors.

This method of generating switchable magnetisation without applying a magnetic field has great implications for the design of new spintronic devices for low power consumption information processing and storage devices.

Novel Magnetoresistive Nanosensor

A team of researchers from HCL and University of Nottingham recently announced the first demonstration of the TAMR (tunneling anisotropic magnetoresistance) and CB-AMR (Coulomb-blockade anisotropic magnetoresistance) nano-devices built in a 5-nm thin (Ga, Mn). As ferromagnetic semiconductor with the active lateral area of only 30 nm × 30 nm. The simplicity of the device made of a single ferromagnetic material and its miniscule dimensions may have great potential in magnetic sensor and memory chip technologies, such as computer HDD (hard disk-drive) read-heads or magnetic random access memories.

The work established the large magnitude of the TAMR and CB-AMR effects and the relationship between these novel phenomena, discovered only within the last year, and the very well-known AMR (anisotropic magnetoresistance) effect. The TAMR nano-devices therefore combine the simplicity of the early magnetic storage devices based on the AMR, the high sensitivity of current giant-magnetoresistance devices which require a complicated multi-layer

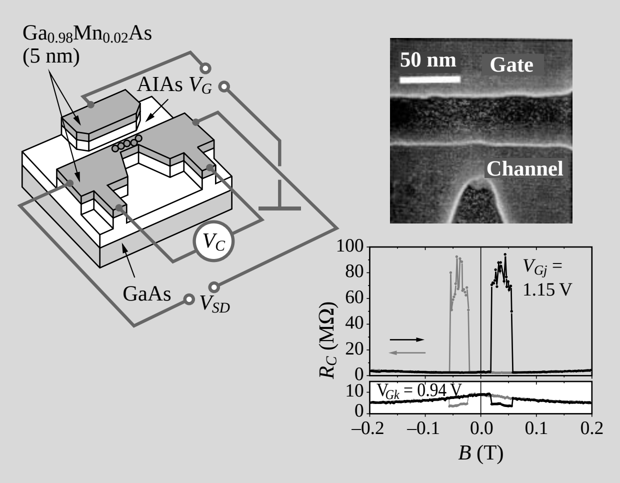

Fig. 3—Schematic View of New Nanoscale Magnetosensor, Real Device, and the Output.
Schematic diagram of the new nanoscale magnetosensor. Inset are a micrograph of the real device, and its electrical output.

design, and prospects for the spintronics industry of downscaling its active parts to several nanometers (see Fig. 3) .

QUANTUM INFORMATION PROCESSING

QIP (quantum information processing) is a new information science based on the principles of quantum mechanics, and includes quantum computing and quantum cryptography. HCL is actively developing the new science into a new IT.

Quantum computing offers a whole new way of processing information, with the possibility of solving certain types of problem that are impossible to solve with conventional computers. HCL is investigating a wide range of approaches to making devices which can be used to build solid-state quantum computers.

HCL and MRC have developed a new photon on-demand device, which converts an electrical pulse signal into an optical signal, where each pulse contains a single photon. The chip is designed to be used as part of a secure data transport system using a technique called quantum cryptography.

Joint projects in collaboration with other research institutions are underway to develop quantum computers and the electronic infrastructure necessary to control them.

Quantum Bits

In a classical computer, the basic unit of information is the bit, which can exist in one of two possible states, e.g. yes/no (or 0/1, as used in binary language). Quantum computers make use of quantum bits (qubits), which can exist in a superposition of both states, e.g. a mixture of both 0 and 1 simultaneously. Qubits are also subject to quantum entanglement. When two or more qubits are entangled, they behave as one system, so that the state of one qubit depends directly on the state of the others. Entanglement has the consequence that the potential processing power of a quantum information system increases exponentially with the number of qubits, rather than linearly in a classical system.

Although the principles behind quantum computing have been established and small model systems constructed, a considerable task still remains to scale these up to practical, working computers. This is certainly worth doing, as it would make possible certain types of computation that are currently impossible using classical computers, certainly impractical within a sensible timescale. A raft of potential applications includes bioinformatics, molecular modeling, codebreaking and encryption. Quantum computers could also be used as simulators to solve quantum mechanics problems.

New Silicon Qubit

HCL announced recently that it has developed a new silicon device for quantum computing: a quantum-dot charge qubit. This structure, based on years of work on single-electronics, is the first step in the development of a quantum computer based on conventional silicon technology.

One approach to building a solid-state quantum computer is by exploiting quantum states of artificial atoms and molecules built in semiconductor quantum-dot systems. The team has demonstrated this with an isolated double quantum-dot as a qubit. The key challenges in producing efficient quantum circuits are to have a system with sufficiently high number of operations within the characteristic coherence time of the qubits, to control the coupling between qubits to form architectures, and to integrate the qubits with manipulation and measurement circuitry. All operations (initialisation, manipulation, and measurement) have been achieved using electrical gates for initialisation and manipulation, and a single-electron transistor for measurement. The scheme gives a very long coherence time (100 times longer than shown in other solid-state implementations), and also provides flexibility in design, since the qubits may be combined in a variety of 2D (two-dimensional) circuits, as in conventional microprocessors. Thus it offers the possibility of scaling-up from one device to a large quantum circuit—a necessary criterion for making a useful quantum computer (see Fig. 4) .

Quantum Computing Platform

A new project, run jointly by HCL, Oxford Instruments Superconductivity, the universities of Oxford and Cambridge and Rutherford Laboratories,

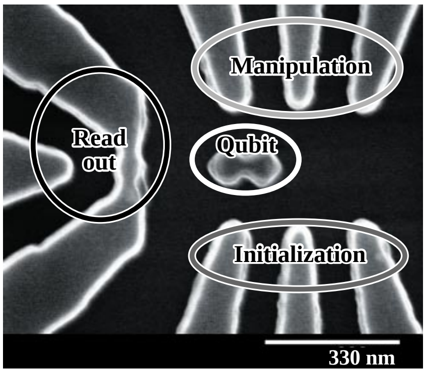

Fig. 4—First Silicon Qubit. The micrograph shows the qubit, gates used to control it, and the readout electrometer.

aims to build a custom platform for running qubits. Hitachi was also the first to demonstrate single-electron memory cells and logic, work which has helped to form the basis of subsequent quantum computing research. The laboratory is currently investigating solid-state systems, using materials including silicon, gallium arsenide and carbon nanotubes.

There are several challenges to be met before a practical quantum computer can be built, with some of the current issues being such as the following:

(1) Algorithm development

There are currently only two suitable algorithms available (although some have already been described for error correction). There is little point in being able to construct the necessary hardware if no software exists that can fully take advantage of the power offered by quantum systems.

(2) Maintaining quantum entanglement

The link between qubits needs to be maintained for long enough to carry out calculations.

(3) Hardware architecture

The structure used needs to be able to produce uniform qubits and to enable the user to manipulate them without interfering with conditions needed for quantum information processing.

Cryogenics may provide a means of achieving a working quantum computer using ultra-low temperatures to preserve quantum coherence and remove any thermal processes that could interfere with computations. Systems will probably have to be tested at mK temperatures, with 4.2 K or lower needed for the first operational computers.

A quantum computing platform will most likely include a dilution refrigerator and a superconducting magnet, together with custom-built electronics working at between 50 mK and 4.2 K. These electronics will act as the control and measurement interface between the computer (working at mK temperatures) and the operator interface (working at room temperatures). One of the major challenges here will be to block out heat leak and electromagnetic interference from wires extending from the room temperature interface into the computer itself. Additionally, the researchers will need to know what the system’s initial entanglement states are, preserve this known entanglement, and also know what processes are taking place during computation.

Although quantum computers are currently in the early stages of development, small model systems have already been demonstrated and the potential power and number of applications remains huge. Indeed, many more applications may become apparent once larger working models have been built and more algorithms have been tested. Although the origins of this discipline are in highly specialised theoretical physics, the potential applications may have dramatic impact on everyone from physicists to pharmaceutical chemists.

CONCLUSIONS

To stay at the forefront of electronic nanotechnology, the laboratories in Hitachi’s global research network are working together on all aspects of future electronic devices. These range from new structures which will enable the continued increase of hard disk capacity through to devices and circuits which look set to revolutionise the very concept of information processing itself.

ABOUT THE AUTHORS

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