Ultimate Control of Electronic Properties in Low-dimensional Semiconductors

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Abstract

Recent progress in semiconductor technology has enabled the development of structures that are scaled down to the nanometer level with high precision by using highly sophisticated nanofabrication and crystal growth techniques. Confining electrons to such low-dimensional nanostructures makes it possible to achieve precise control of electrons as particles as well as waves. The Feature Articles in this issue review our recent research activities involving low-dimensional semiconductor devices that will be applied to achieve innovative electronics in future science and information and communication technologies.

Keywords: low-dimensional semiconductor, single-electron device, quantum device

1. Introduction

Nowadays, we are surrounded by many electronic information processing tools such as personal computers (PCs) and smartphones that quickly process enormous amounts of information delivered through high-speed networks all over the world. All of these information and communication technology (ICT) elements have become vital lifelines to support our daily life and business. One of the key technologies for sustainable development of our ICT society is semiconductor technology. A semiconductor is a material that has electrical conductivity properties between those of conductors (metals) and insulators. They include silicon used for large-scale integrated (LSI) circuits, compound semiconductors used for laser diodes in optical fiber telecommunications, and nitride semiconductors developed for white light-emitting diodes (LEDs). One of the great features of semiconductors is that they can switch electric current or emit light at a high energy-efficiency level as well as aid in the downsizing of components.

Remarkable progress has been made in semiconductor technology in the last several decades through comprehensive research on high-quality material growth, device fabrication, and device physics aimed at improving design and performance. If we take a look at the history of the LSI circuit chip, which works similarly to the central processing unit, or *brain*, of a PC, we can see that improvements in performance have been achieved year-by-year by packaging a larger number of transistors whose sizes have been miniaturized using micro- and nano-fabrication techniques. The number of transistors per chip currently exceeds 1 billion, which is on the same order as the world population.

However, while performance has grown according to this simple scaling rule, the power consumption of the chip has also increased significantly and is becoming a serious problem in terms of the environmental impact and energy costs. As a result, there are rising technical demands and expectations for low-power devices and circuits that operate on novel principles and concepts. Semiconductors, on the other hand, have attracted much attention as a material for basic research on solid-state physics. Various structures and devices that are artificially fabricated using advanced nanofabrication processes have provided an excellent platform to advance the frontiers of physics. Therefore, one can say that semiconductor research is a field where science and technology are most beautifully united. In this respect, if we can control new physical phenomena that manifest in novel semiconductor structures, we will be able to create new electronics that achieve the ultimate functionality and performance, which are totally different from those of simple current switches and light-emission devices. This has motivated us in the Physical Science Laboratory of NTT Basic Research Laboratories to conduct research on semiconductors to explore their applications and new physical properties in order to achieve future innovation. The main results of our recent activities are reviewed in these Feature Articles.

2. Electronic properties of low-dimensional semiconductors and their ultimate control

One of the key players in the functioning of semiconductor devices is an electron that moves around freely in the semiconductors. For example, the most fundamental function of transistors in LSI circuits is to switch electric current by controlling the flow of electrons in semiconductors. This function is often considered similar to stopping and starting the flow of water. However, this is approximately true only if the size of the semiconductors is large enough. It is now well known in quantum mechanics that an electron—which is an elementary particle with a minimum electric charge of approximately 1.6×10^{-19} Coulombs—behaves as a wave with the de Broglie wavelength. When the electron is confined in nanometer-scale structures artificially constructed through crystal growth of semiconductor heterostructures and/or nanofabrication, which are often called low-dimensional semiconductors, its quantum mechanical nature appears as a *wave*. Furthermore, even as a particle, electrons behave very differently since electrons confined in a small space have a large repulsive Coulomb force between them due to their negative charge, although the amount of the charge is small. This is in contrast to the case when electrons move around freely in a larger space. We can utilize such an electron-electron interaction to manipulate and control individual electrons. In addition, electrons have internal states called *spin* as well as the corresponding magnetic moments. Spin has been applied practically in magnetic memory constructed of ferroelectric metals, but it has also attracted attention recently as a potential information carrier in new information processes. This is because the use of the flow of spin, that is, spin current, could prevent energy dissipation and heat generation, which are inevitable when electron current—the flow of charge—is used for information processing.

As described above, electrons in low-dimensional semiconductors show a variety of unique properties based on quantum mechanics, electron-electron interaction, spin, and their combined phenomena. Such properties are spawning research subjects from both pure physics and engineering for future science and technology. Typical structures of low-dimensional semiconductors are often categorized into quantum wells (two-dimensional planar structures), quantum wires (one-dimensional linear structures), and quantum dots (structures confined in all directions, such as cubes and spheres, thereby called zero-dimensional structures).

A zero-dimensional structure, in which electrons can be regarded as particles but are dominated by the electron-electron Coulomb interaction, is sometimes called a single-electron island because we can store electrons in it one by one. The research on low-dimensional semiconductors has a long history, and many studies have been done on their physics as well as device applications such as single-electron devices. Recently, technical progress achieved in both high-quality crystal growth and sophisticated nanodevice fabrication has been opening up the possibility of the ultimate control of electrons. The article "High-speed Single-electron Transfer toward High-accuracy Current Standards" [1] describes fast and accurate control of electrons as particles achieved with silicon nanowire devices. One of the targets of this study is to achieve electric current standards for metrology. If we can generate accurate current based on the clocked transfer of single electrons, it may be possible to complete the so-called metrological quantum triangle of electric standards. The current standards remain to be developed as the final element in addition to the already existing quantum resistance and voltage standards based on semiconductor devices and superconductor devices, respectively.

The article "Noise in Nanometer-scale Electronic Devices" [2] describes thermal noise in ultimately miniaturized electronic devices, which is investigated based on the resolution of single electrons. A silicon nanotransistor with ultra-high charge sensitivity is utilized to read out the voltage noise in an ultra-small dynamic random access memory (DRAM) and is used to measure the quantized values of fluctuating voltages resulting from the thermal fluctuation in the number of electrons in the charge node of the DRAM. We analyze the thermal noise and determine how it deviates from that expected from the conventional electric circuit model in the tiny device.

The efforts to make silicon light emissive are introduced in “Gate Tuning of Direct/Indirect Optical Transitions in Silicon” [3]. It is well known that silicon is categorized into a material with an indirect optical transition and has low efficiency in terms of light emission. What is strikingly unique about this research is that the efficiency of the light emission is electrically increased by strengthening the direct optical transition. In fact, the reason we are able to do this is not yet clear, but the results suggest that the electron wave is strongly scattered in our quantum well structures with a specially prepared silicon/silicon dioxide interface. This is really amazing because it proves that there are still unexplored electronic properties in silicon, which already has a long history of research.

The studies above focus on silicon, but gallium arsenide (GaAs) is the focus in “Microscopic Probing of Crystalline Electrons Using Magnetic Resonance” [4]. In this work, we observe for the first time the crystallization of electrons in a two-dimensional system in a high magnetic field, which is similar to the crystal of a solid-state material in which atoms are regularly allocated in space. This takes place because electrons tend to avoid each other and find their places in an adequately spaced arrangement. In terms of physics, this corresponds to the situation where the energy of the electron-electron interaction is higher than that of the kinetic motion of electrons. Using high quality film grown based on our crystal growth technology was essential in confirming this clean electron system in two dimensions.

In “Semiconductor Quantum Structures with Single-atom Precision” [5], a unique method for fabricating low-dimensional semiconductors is introduced. It is quite different from the standard technology employing lithography (often called the top-down approach) and is used to construct an ultra-small structure by placing atoms one by one (the bottom-up approach). When a compound semiconductor is used in which the wave-like nature of electrons is prominent, the shape of the electron wave confined in a quantum-dot structure is clearly observed. This method enables us to control the shape of the electron very precisely since our structure is accurately built using the atom as a building block.

The last article, “Creating a Topological Insulator Using Semiconductor Heterostructures” [6], describes the investigation of a topological insulator, a subject of great interest in solid-state physics. Topology is originally a term used in mathematics, but a topological insulator refers to a unique material whose surfaces or edges are electrically conductive, although there are insulators in the internal parts. It is theoretically predicted that by using such a low-dimensional electron system at the edge of the material, we can generate a flow of magnetic moments of electron spin (called spin current) without any flow of electrons as charges. If this is achieved, it may lead to innovative techniques enabling information to be transmitted with almost no energy dissipation.

3. Future prospects

As indicated above, the research on semiconductors is continuously driven by both scientific and technical interests and is approaching a level where precise control of electrons and atoms will become a reality. These goals have been elusive until now. We believe that we will be able to create innovate semiconductor devices that will surpass existing devices in performance and function by further improving the controllability of electronic properties in low-dimensional semiconductors created through our advanced fabrication and crystal growth technology. The Physical Science Laboratory at NTT Basic Research Laboratories thus continues to conduct research to develop novel electronics for the future information technology society such as highly accurate and highly sensitive electronics and novel information transmitting and processing devices based on new quantum mechanical phenomena.

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