Research Frontier of Quantum Computers

Hiroshi Yamaguchi

Abstract

This article introduces quantum computing, the topic of the Feature Articles in this issue. More than ten years have already passed since the study of devices for quantum computers began. During this time, the technology for manipulating the quantum state of the basic element, the qubit, has greatly improved, but fundamental problems have also been revealed. The Feature Articles in this issue review new attempts underway in our laboratories to overcome such problems.

1. Development and application of quantum physics

The quantum computer has been attracting attention because of its potential ability to perform extremely high-speed signal processing. More than ten years have passed since the start of competitive studies of hardware for quantum computing. The basic element for configuring a quantum computer is called a quantum bit, or qubit. Research toward achieving an ideal qubit has been actively pursued using systems having various physical units.

The quantum computer operates according to the principles of quantum mechanics, a fundamental theory of physics. Quantum mechanics describes behavior in the natural world very differently from Newton's classical mechanics, although classical mechanics is the source of our common sense. For example, the statements "mechanical systems all have the aspects of both waves and particles" and "dynamical systems can all be present at the same time in multiple locations" arise as a consequence of quantum mechanics. These ideas indicate that a physical system has inherent multiplicity, referred to as quantum superposition, and this multiplicity of physical systems is the key mechanism for massively parallel computation in a quantum computer.

Accepting these ideas also raises questions of a philosophical nature: Are our bodies also like waves and can they exist simultaneously in two places? How about the human mind? Can it also exist in two places at the same time? And if so, then if it dies in one place, does it also die in the other place? Since the basic theoretical framework of quantum mechanics was established nearly a century ago in the 1920s, there have been ongoing discussions about questions such as these. After serious debate over the course of many years, physicists have come to believe that the theory is infallible. To date, they have found that all experimental observations are successfully explained by quantum mechanics.

From the viewpoint of engineering applications of quantum mechanical phenomena, quantum mechanics has led to the creation of innovative technologies such as semiconductor devices and lasers. For instance, the band structure in a semiconductor could not exist without quantum-mechanical effects, and lasers would not work without quantum mechanical interaction between light and matter. However, technology that uses an essential aspect of quantum mechanics, such as the idea that an electron can exist in two places at the same time, has been explored only very recently in the form of quantum information technology, such as quantum computers and quantum cryptography.

We have been studying microfabrication and nanofabrication technologies for the development of electrical and optical semiconductor devices. As a new application, the research of semiconductor and superconductor devices, where the quantum mechanical nature appears, was initiated more than ten years ago (**Fig. 1**). Now, it is even becoming possible to control the quantum mechanical multiplicity in these structures. Major technological advances using the essence

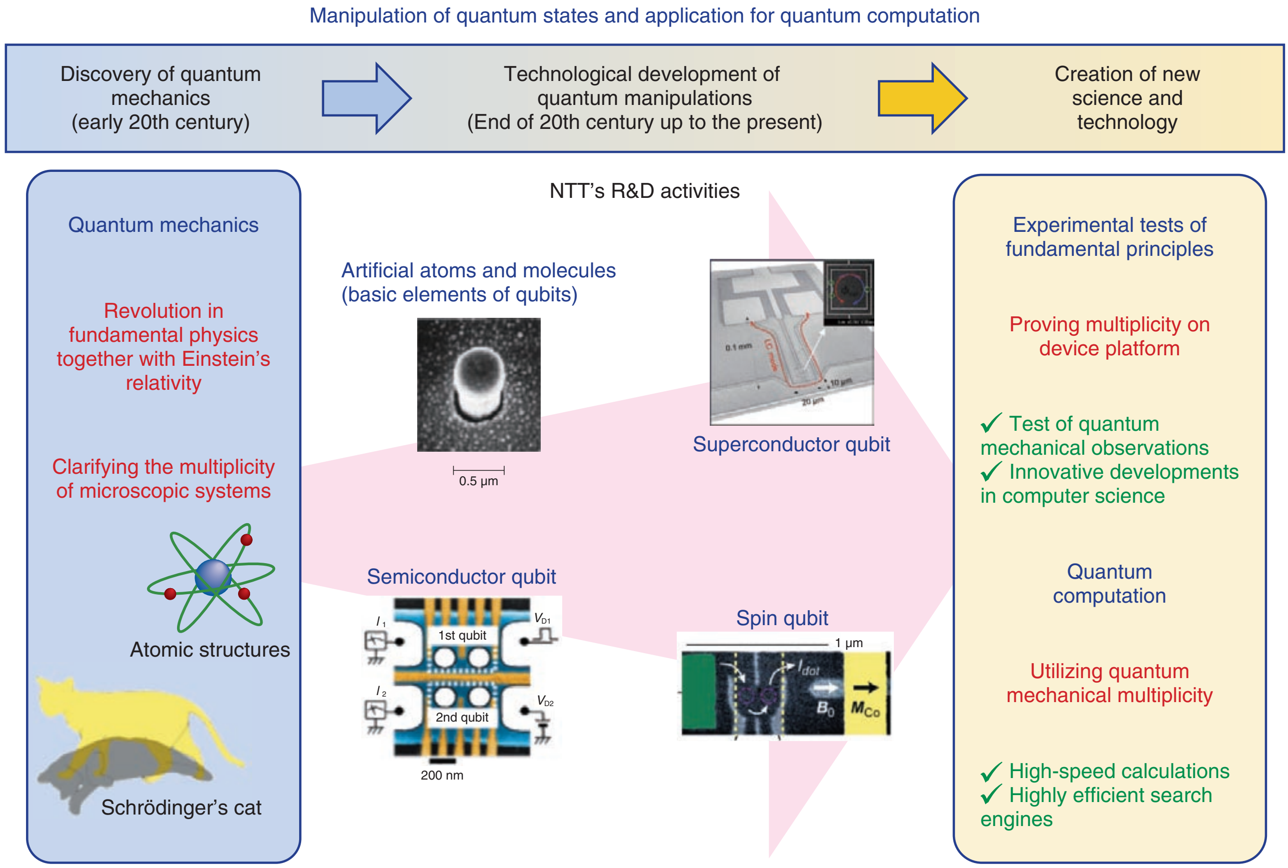

Fig. 1. From the discovery of quantum mechanics to its application.

of quantum mechanics promise ultrafast and highly energy efficient database searches and calculations. They can be used in applications such as the discovery and design of new materials and pharmaceuticals.

2. Challenges of quantum computer research

As a result of various attempts over the past ten years, a technique for precisely controlling the superposition of qubit states "0" and "1" has progressed significantly in individual studies. Simultaneously, serious problems have been encountered as we proceed toward the development of more realistic quantum computers. One of the biggest problems is that it is not easy to extend the present scheme to multibit systems. For a *classical* computer, once you have completed the development of one element (such as an OR gate or AND gate), joining elements to construct a multibit system is not difficult. The basic elements linked by wiring perform the combination of their operations and there is no essential problem in multibit operation. On the other hand, qubits face an essential problem concerning multibit operations. That is, the quantum superposition cannot be maintained for a long enough time to perform multibit operation. There is a limit to the amount of time for *coherent* operation. With the current level of technology, it is not too difficult to manipulate the quantum state once, but when we try to run it multiple times, the quantum state is easily broken and the operation cannot continue.

This problem had been regarded as important from an early stage and research has been seeking to find a qubit that maintains the quantum superposition state for a longer time. Various different physical systems of qubits have been devised and each has been found to have both advantages and disadvantages. One system allows very fast computation but the quantum state immediately becomes corrupted; another is not good at bit operation but the quantum state can be maintained for a long time. Moreover, some systems are well suited to the combination of multiqubit gates, while others are not, although they have excellent performance in single-qubit operation. Therefore, constructing a hybrid system consisting of different types of physical systems with different advantages is regarded as the right direction, rather than proceeding to force the construction of the best system with qubits of only a single type.

The Feature Articles in this issue introduce NTT's recent research related to a variety of different types of qubits. These studies are at different stages of research, ranging from confirming operation as a qubit to just exploring basic physical properties. Below, I briefly describe the characteristics of each quantum system.

3. Various physical systems studied for configuring hybrid qubit systems

3.1 Superconducting circuits

Superconductivity is a phenomenon in which the electrical resistance of materials vanishes at low temperature. Current flowing through a circuit loop made of superconductors never stops because the material has zero resistance. This current is very stable, and we are attempting to use it to represent a quantum state. The superconducting qubit is one of the most successful and advanced systems among solid-state quantum devices.

The basic structure of the superconducting qubit is shown in **Fig. 2**. The parts for *disturbing* the superconducting current flow, called Josephson junctions, are formed on a looped circuit consisting of superconducting aluminium. These junctions mix the currents flowing clockwise and anticlockwise to achieve a quantum superposition state, where the current simultaneously circulates in two opposite directions. The superconducting circuit offers very good quantum superposition control, but trying to configure multibit operations only with superconducting qubits has been a major challenge. Instead, we have recently been attempting to integrate the circuit with *quantum memory* implemented in other quantum systems. More specifically, we are working to study the quantum spin states used as the memory with defect complexes called NV^- centers in diamond. In addition, a major issue is how to read out the qubit state without destroying it because the signal induced by the current is very weak. This set of Feature Articles introduces studies addressing these two challenges.

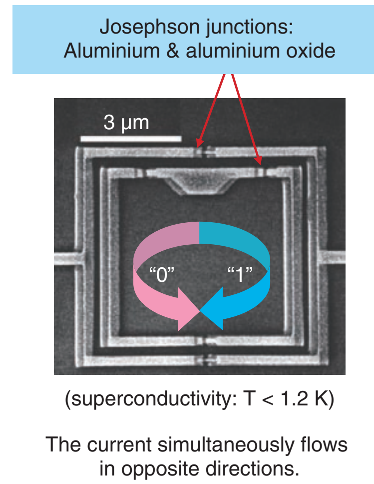

Fig. 2. Superconducting qubit.

3.2 Electron spin

Spin is a quantum mechanical property of elementary particles such as electrons and protons (**Fig. 3**). It is a kind of angular momentum that the particle possesses in itself, so spin is often regarded as rotation about an axis. Quantum theory combined with Einstein's theory of relativity requires an electron to eternally exhibit angular momentum, i.e., the rotation is sustained forever. This is similar to a superconducting current and can represent a quantum state depending on whether the clockwise or anti-clockwise direction of rotation is sustained.

Electron spin is used in several applications, the most well-known of which is magnets. The properties of a magnet could not be generated without electron spins. We can intuitively understand this by considering electron rotation to induce a kind of rotating current that generates a magnetic field like a coil or solenoid.

The possibility of obtaining long-lived quantum states for spin qubits has been pointed out. For example, the spin state in an NV^- center in diamond is reported to be maintained for a time on the order of milliseconds. This is longer by two or three orders of magnitude than that in solid-state qubit systems, so its use for quantum memory is highly promising. An article in this issue describes a study on controlling electron spins by applying a voltage to semiconductor devices and one that covers quantum memory using NV^- centers.

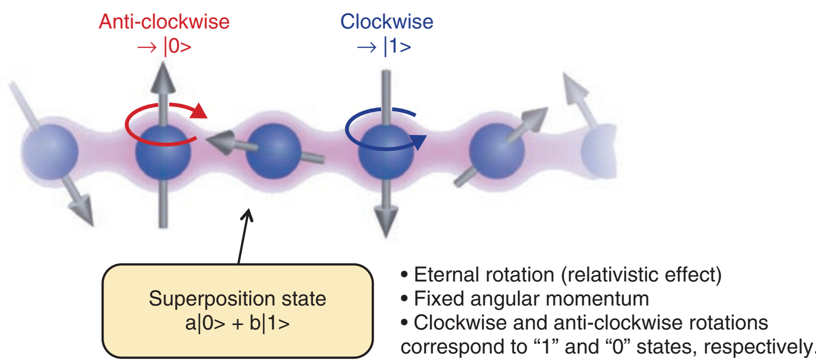

Fig. 3. Schematic explanation of electron spin.

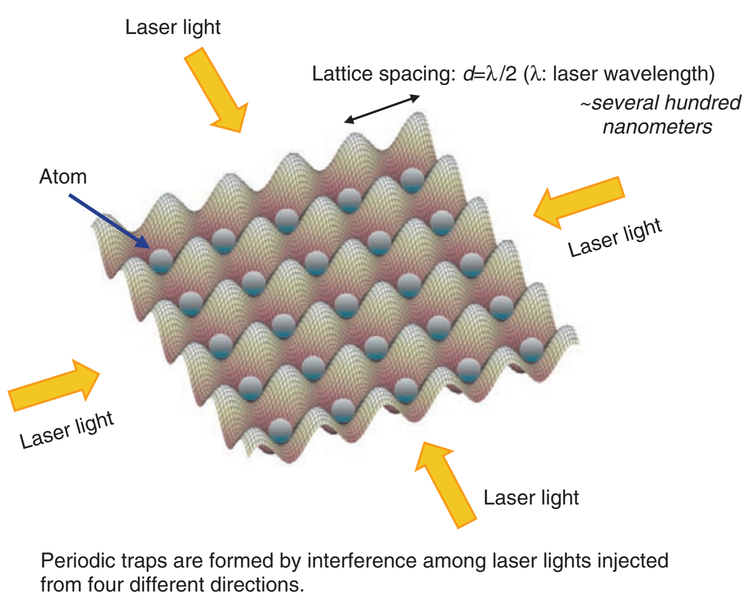

Fig. 4 Schematic illustration of optical lattice.

3.3 Cold atoms

Until recently, cold atoms had been considered to be unsuitable for developing solid-state quantum computers because they are not available in solid form, although they can sustain quantum states for a very long time. However, in recent years, they have become strong candidates for solid-state qubits following successes in integrating cooled atoms on a piece of solid material, called an atom chip.

The atom is one of the physical systems where quantum phenomena were confirmed at a very early stage in the history of quantum mechanics. This is because atoms in gas are isolated from each other, which can maintain the quantum mechanical nature. However, if you try to control the quantum state, the atoms move too rapidly to detect and control the individual quantum states.

The solution to this problem is to cool the atoms. The rapid motion is caused by thermal energy, so lowering the temperature can confine the atoms in a limited space. In practice, it is not easy to cool atoms down to temperatures where atomic motion is sufficiently suppressed, but a technique called laser cooling is promising for this purpose. This issue introduces a method for applying laser cooling in an attempt to construct a regular lattice of cooled atoms (**Fig. 4**).

4. Diversity and future of quantum technologies

Einstein's famous theory of general relativity, proposed in 1915, provided many extraordinary predictions, such as that time passes at different speeds on the ground and in space, and it completely changed our world view. Although the theory has had a great impact on the scientific community, people believed until recently that it would not be of practical use in technologies relevant to our daily life because its influence is extremely small. However, the global positioning system (GPS) that we currently use would be inaccurate if its design did not take into account the theory of general relativity. Advances in technology are surprisingly fast, and technologies that were initially thought to be impossible spread very quickly once they have been developed.

As mentioned already, nearly a century has already passed since the discovery of quantum mechanics but the study of how to use its essence in practical technology has begun only very recently. In that sense, the study of the quantum computer is still just beginning and it will certainly take a long time to come to fruition. Research scientists love to try to achieve major breakthroughs, and the research activities presented in the Feature Articles in this issue are examples of such attempts. By combining the techniques covered here, we may be able to create quantum computers with excellent performance in the near future. Alternatively, some researchers expect big developments in applications of quantum phenomena completely different from the quantum computer. Quantum mechanics is very different from classical mechanics, which governs the basic principles of current technology, and it has such a wide diversity that the quantum computer may well be only one example of its applications.

Hiroshi Yamaguchi

Senior Distinguished Researcher and Group Leader of the Nanostructure Technology Research Group, NTT Basic Research Laboratories.

He received the B.E. and M.S. degrees in physics and the Ph.D. degree in engineering from Osaka University in 1984, 1986, and 1993, respectively. He joined NTT Basic Research Laboratories in 1986. His current interests are micro/nanomechanical devices using semiconductor heterostructures. He has been a guest professor at Tohoku University since 2006. He is a fellow of the Institute of Physics and a member of the Japan Society of Applied Physics, the Physical Society of Japan, and IEEE.