# R&D Spirits

## Focusing on "Single Electrons" toward Quantum Computing

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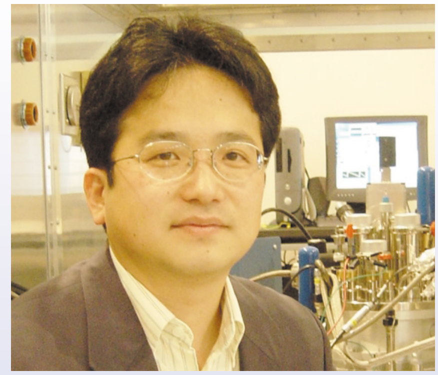

Research on quantum computing has been progressing throughout the world with the aim of achieving ultrahigh-speed processing through parallel computation. As part of this world-wide research effort, the Physical Science Laboratory at NTT Basic Research Laboratories is taking the approach of using "single electrons." With the research period expected to span several decades, what stage is this research currently at and what is its final objective? We put these questions to Distinguished Technical Member Toshimasa Fujisawa, a key figure in this research and the winner of the 2003 Sir Martin Wood Prize.

### Taking on the nano-level world with a view several decades into the future

*—Dr. Fujisawa, could you give us a brief outline of your current research?*

Well, my research is part of a field that is generally called "nanotechnology" and I work on determining how accurately a single electron can be controlled and measured on a short timescale of a certain duration [1]. Electrons have been used in electronic equipment and other devices as carriers of energy, charge, or information, and they have usually been controlled in the form of "voltage" or "current." But if electrons can be confined to an extremely small space, it should be possible to control them individually. Then, a single electron will start behaving as a wave as opposed to a particle. The objective of our research is to investigate the behavior of single electrons in semiconductors on the nanometer scale and to connect our findings to applications that can make use of the properties that we discover.

A variety of application themes can be considered here, but at present, I am targeting two specific applications. The first is a relatively near-future application: an ultrahigh-precision ammeter that can count individual electrons. Since an ammeter is the most basic of measuring instruments, the ability to accurately measure an extremely small current, say on the order of only 1000 electrons per second, would undoubtedly be useful in many fields. The second application is quantum computing that will treat a single electron as one bit of information and exploit its superposition state (**Fig. 1**). But computation cannot be achieved with only one electron—we need to increase the number of electrons while maintaining control of each and every one. As we have just reached the stage where a single quantum bit, or qubit, can be achieved, our research has just gotten under way.

*—In what way do you think this research can contribute to society?*

Quantum computing should enable ultrahigh-speed information processing through parallel computation (**Fig. 2**). At present, it is expected to be used mainly in scientific fields such as for specialized database searches and quantum physics simulations. But this research field has just begun, so achieving our overall objective of a 1000-qubit-class quantum computer could take several decades. While setting our final

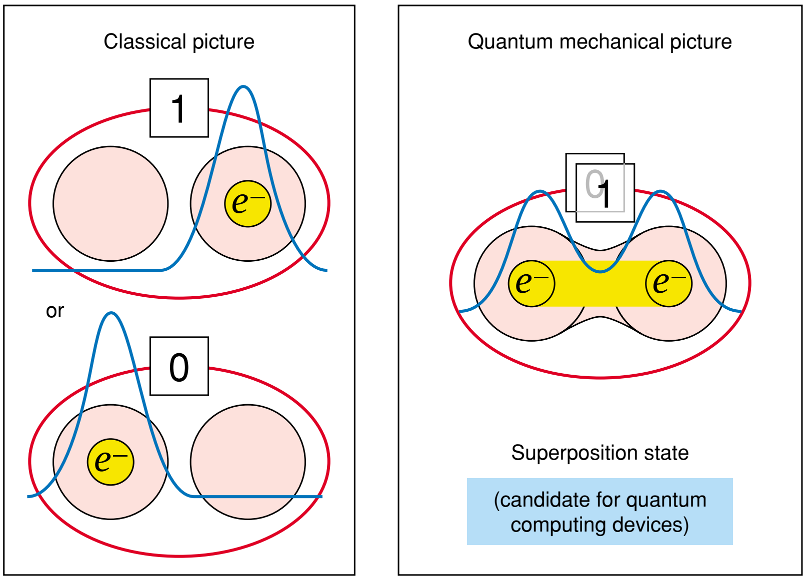


Fig. 1. Classical bit (left panel) and quantum bit (right panel) in a double quantum dot. A quantum mechanical state can take any superposition of the two classical states. This superposition is a key to quantum computation.

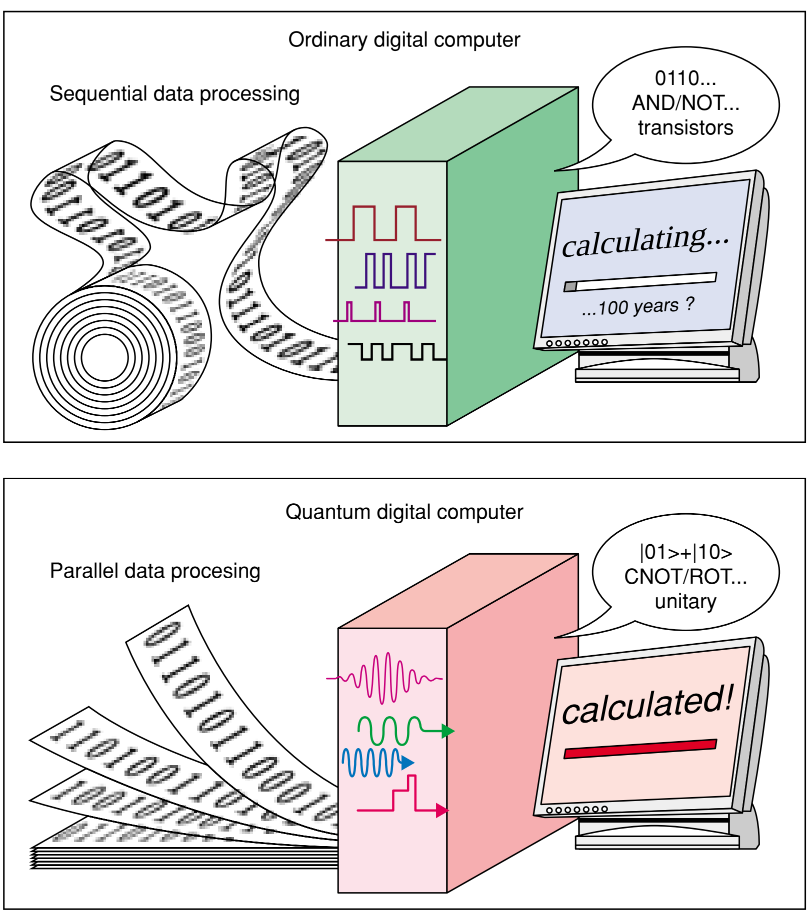


Fig. 2. Comparison of ordinary digital (classical) computer (upper panel) and quantum computer (lower panel). In the quantum computing scheme, data prepared in a superposition is processed in parallel.

target as quantum computing, our plan is to develop applications like the ammeter that can contribute to society in the mean time.

*—What technology is associated with controlling single electrons?*

There are two main technical aspects to our research. The first concerns semiconductor nanofabrication technology, in which we try to determine the extent to which small structures can be fabricated at will. The second concerns measurement technology, in which we try to determine the maximum level at which precision measurements can be made. Nanofabrication technology has been an NTT specialty for a long time and our work is world class, but our measurement technology lags somewhat behind. This is because measurements of quantum mechanical effects are made in an extremely low-temperature environment to reduce noise as much as possible, something with which NTT did not have much experience. Therefore, we set out to improve our technical abilities through joint research with European research institutes having a history in this field. Through this effort, we achieved world-class measurement capabilities in single-electron control.

*—What are some current problems?*

A major problem is the noise that occurs during measurements. We must connect the low-temperature environment where the measurements are made and the laboratory where the measurement equipment is located. However, thermal fluctuations in the measurement equipment operating at room temperature can be transmitted as noise over the wiring. Removing that noise is our biggest challenge at present. While electrodes are essential for controlling qubits and for counting, they are also factors in the generation of noise. There is consequently a tradeoff between reducing noise and maintaining control. This is a problem that bothers not just us but also other researchers around the world.

*—What direction is this research taking?*

Most of our energy is concentrated on creating 2-qubit states. If this can be done, we expect very interesting research to follow even in physical terms. Above all it will let us prove whether the quantum-mechanical behavior of electrons described by theory can actually be measured and controlled. In this regard, we are particularly interested in quantum entanglement experiments. Electron spin (rotation) is expressed by the direction of rotation with clockwise rotation indicated as “up” and counter-clockwise rotation as “down.” Given two electrons, there are four electron-spin combinations: up-up, up-down, down-up, and down-down. In “quantum entanglement,” however, it is possible to create a state with correlation in which an up spin in one electron forces the other electron to have a down spin. While research on this state is progressing through experiments using photons, its behavior for electrons in solid materials is still unclear. It appears that quantum entanglement is becoming a very important research theme.

As for applications, the establishment of basic computation techniques between one qubit and a pair of qubits can be envisioned. If this can be achieved, I believe the door to quantum computing will be wide open.

## Participating in joint research with overseas institutions and linking up with industry, government, and academia

*—Dr. Fujisawa, what trends are taking place in quantum computing in Japan and overseas?*

Research with quantum computing as a specific target is being performed here and there, and academic societies and research conferences concerned with quantum computing are increasing. Hardly a week goes by without a meeting on quantum computing being held somewhere.

As for world trends, many research institutions are engaged in quantum-computing research based on superconductors initiated by Japanese electronics manufacturers. These include the Saclay research laboratories in France and the National Institute of Standards and Technology (NIST) in the United States. In contrast, semiconductor-based research, which is our type of research, is not as prevalent, but it does cover a wide range of approaches from the use of optical techniques to electrical techniques, the latter being our approach. I would say that the research being conducted at Delft University in The Netherlands and at Harvard University in the United States is the most similar to ours in terms of electrically controlling electrons in semiconductors.

*—Are you engaged in joint research with overseas research institutions?*

In recent years, basic research has taken on an international style where advances are made through collaboration. A single team is limited in what it can accomplish by itself. We have also been collaborating with a number of research institutions. For example, a student from Denmark is currently working in our group, and we have a delicate relationship with Delft University in The Netherlands that includes both collaboration and competition. I myself was a visiting researcher at Delft University for just under a year, six years ago.

*—Have you been involved in any other activities or scientific exchanges outside NTT Laboratories?*

Well, as part of a project linking industry, government, and academia, I have been serving as a visiting associate professor in the graduate school of Tokyo Institute of Technology. As for scientific exchanges, last year I received the Sir Martin Wood Prize, which entitled me in June of this year to be an observer and make research presentations at four British universities: Oxford, Cambridge, Nottingham, and Southampton. This prize, which is named after the founder of Oxford Instruments, a U.K. manufacturer of scientific instruments, is given annually to a researcher under the age of 40 working in condensed matter science at a Japanese research institution. A lecture trip to the UK is given as a supplementary prize to promote scientific exchange and research activities between the UK and Japan. By the way, something that I was particularly impressed with on this visit to the UK was the importance attached to tradition. This was true even for research equipment. In addition to new equipment, I also saw a number of traditional but amazing devices that were used carefully with great respect. At Oxford University, for example, there is a pulse magnet that produces a magnetic field stronger than even that of a superconducting magnet, and it is also treated with much importance. I admire this attitude immensely.

## Advancing research step by step while incorporating new ideas

*—Could you tell us about your major field of study at university? And what was your objective in entering NTT Laboratories?*

My research theme in school was impurity levels in semiconductors. A semiconductor functions because intentionally doped impurities contribute conductive electrons. Impurities, however, can also give rise to a defect level in which conductive electrons become trapped and no longer contribute to conduction. This is called the "impurity level." I researched it for five to six years until receiving my doctorate. Though both concern semiconductors, my past research was based on a materials-oriented approach, which differs from my current research. I enjoyed studying impurity levels by this approach, but I also developed an interest in mesoscopic transport at the same time. The word "mesoscopic" means a level between the macroscopic level of typical semiconductors and the microscopic level of atoms. It's a research area that examines how electrons behave within a very small structure. At NTT Laboratories, this field of study is promoted, and I was fortunate to be able to enter the company and pursue the research that I desired. I have been involved with this research ever since.

*—What kind of research in particular have you been engaged in up to now?*

At first, I was involved with semiconductor fabrication technology, and I researched means of creating nanostructures by focused ion beam implantation. I then moved on to materials-properties research in relation to ballistic conduction, in which the reduced level of semiconductor impurities enables electrons to propagate without being scattered. These studies expanded into research of quantum dots that completely confine electrons (**Fig. 3**).

Then, as the next step in this research, I considered observing what happens when a quantum dot is irradiated with light. In general, there are two approaches to quantum-dot research: using electrical conduction and using light. Nevertheless, I thought that I might observe something interesting if I tried combining these two approaches. However, electrical conduction and light have completely different energy scales, which means that they cannot be combined directly. I therefore decided to use microwaves instead of light. Because the energy intervals of quantum dots are exactly equivalent to microwave energy, I thought that I might be able to excite electrons inside a quantum dot by irradiating it with

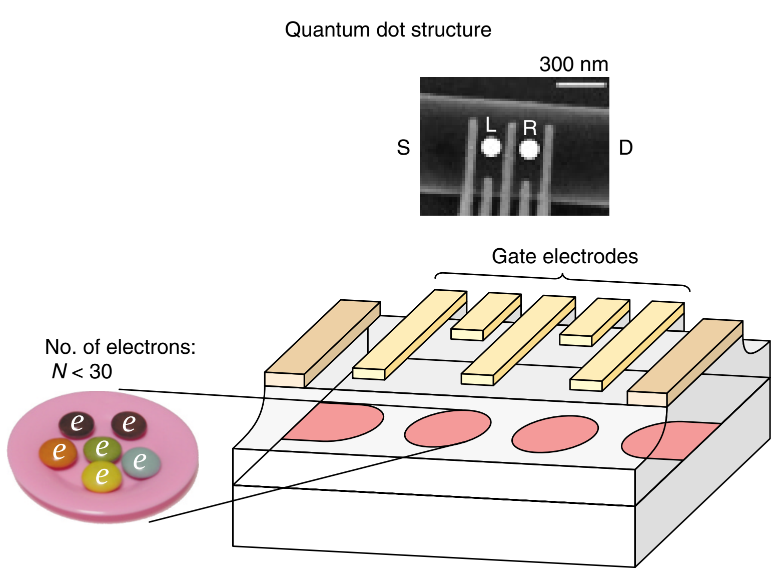


Fig. 3. Double quantum dot structure fabricated in a semiconductor heterostructure.

microwaves. This marked the beginning of my research on electron behavior when giving a quantum dot a time-dependent potential by microwaves.

*—What brought about your research on quantum computing?*

My research on quantum dots using microwaves got under way in 1998, just around the time that quantum computing came to be discussed in the research community. As various quantum computing proposals were made and basic experiments performed, I had a vague feeling that maybe my research could be connected to quantum computing, and I began research on achieving quantum bits.

*—What have you been pursuing through your research?*

Well, to be honest, I can't say that we began our research with a clearly defined vision. Rather, in the area that we were interested in, we developed our theme one step at a time while incorporating new ideas and solving any problems that we encountered along the way. That is how we arrived at the present. In our present research, we first devoted all our energies to achieving control of individual electrons. This has since become commonplace, although it is still not perfect. As we work to improve the quality of such control, perhaps we will make new discoveries, even if only qualitative in nature.

## Drawing the future by searching out unforeseen fields

*—Dr. Fujisawa, how do you think your research will develop five and ten years down the road?*

The kind of basic research that we deal with requires a relatively long time to produce tangible results, so I don't think five or ten years is really enough time for such results to appear. On the other hand, basic research gives researchers the possibility of "drawing" a blueprint for the future, which can be quite exciting. But as the next step in our research, we are considering the application of scanning probe microscope technology to control electrons both temporally and spatially. So far, we have been able to control the number of electrons and control them temporally, so our next task is to control them spatially. Our ultimate research goal is to establish various control technologies so that we can make electrons do whatever we want.

*—Is there anything of special concern for you as a researcher?*

Well, to begin with, I think researchers tend to confine themselves to narrow fields in order to establish a specialty. Of course, it is important to decide on a specialized field of study, but I don't think your research will have much impact if you do not keep an eye on the outside world. Even research results produced after much effort will not penetrate very far if their value cannot be conveyed to society at large. For this reason, I have recently been striving to express specialized concepts in an easy-to-understand manner so that a greater number of people can comprehend our research activities.

*—How has NTT Laboratories been advantageous for you?*

To be able to become involved in both basic research and application-oriented research has been truly wonderful for me. I think it would not be an exaggeration to say that NTT is currently the only private enterprise in the world pouring so much effort into basic research. While amazing research can be performed at universities and other research institutions, it is private enterprise that excels at returning the fruits of research to society. We are always working to return something to society, even if that "something" is in the distant future. Another advantage of NTT Laboratories is the freedom that is generally given to researchers in their work. I feel very lucky to have worked in such an environment.

*—In closing, could you tell us something about your future aspirations?*

Yes, of course. As I touched upon earlier, research sites are increasingly interacting with the industrial, government, and academic sectors and with their counterparts overseas. NTT Laboratories is likewise promoting many collaborative projects with industry, government, and academia. My position as a guest associate professor and lecturer at Tokyo Institute of Technology has enabled me to provide guidance to students. In addition to my desire to continue with my own research, I would love to see my research used as educational material for students, the researchers of tomorrow. My hope is that activities such as these will help to expedite the spread of research results that are beneficial to society. That would be wonderful.

## Reference

[1] T. Fujisawa, "Quantum Information Technology based on Single Electron Dynamics," NTT Technical Review, Vol. 1, No. 3, pp. 41-45, 2003.

**Interviewee profile**

■ Career highlights

Toshimasa Fujisawa received the M.S. and Ph.D. degrees in engineering from Tokyo Institute of Technology in 1988 and 1991, respectively. His Ph.D. thesis was entitled "DX centers in III-V semiconductors". He joined NTT Basic Research Laboratories in 1991. He became a Senior Research Scientist in 1995 and a Distinguished Technical Member in 2001. He was a visiting researcher at Delft University of Technology from Dec. 1997 to Aug. 1998. He has been a Guest Associate Professor at Tokyo Institute of Technology since June 2003.

■ Major awards

Sir Martin Wood Prize, Millennium Science Forum, Nov. 2003.