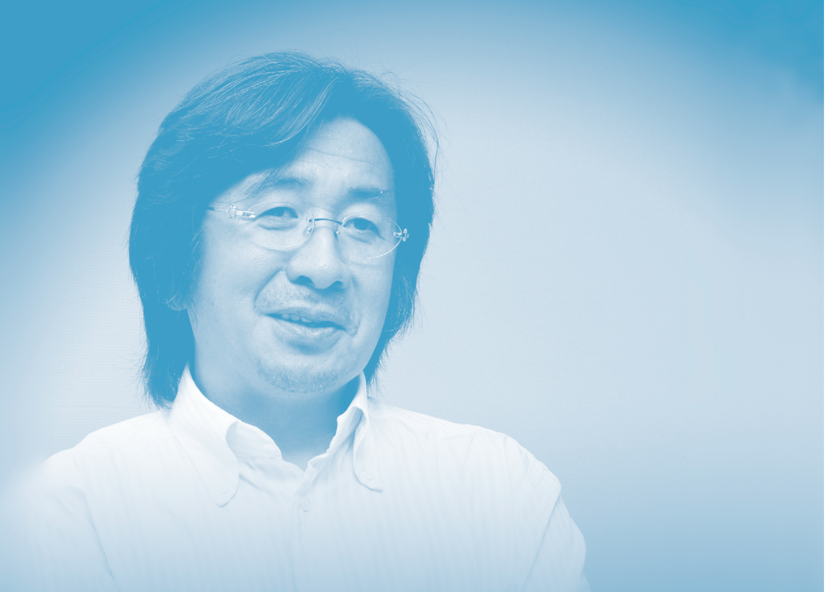
Road to the Quantum Computer Now Found!

Success in 2-bit logic computations using solid quantum bits



Dr. Jaw-shen TSAI
Research Fellow
Fundamental and Environmental Research Laboratories

"The quantum computer" is attracting great expectations and attention for its innovative operating principles and its capability for solving problems that have been difficult to solve for traditional computers. Although, until only a few years ago it was said that its implementation would take a hundred years or so, several promising research results that seem to approach realization are now being announced from all over the world. Among these results, the achievements made by NEC's Fundamental and Environmental Research Laboratories are highly evaluated as forming the forefront of the field. The details of this research are difficult for the layman to understand but in order to help explain it, we have interviewed Dr. Jawshen Tsai, a Research Fellow at the laboratory about the significance and the challenges of his research.

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What is "a quantum computer"?

Dr. Tsai works at NEC's Fundamental and Environmental Research Laboratories in Tsukuba, Ibaraki Prefecture, Japan. When we pass the corridor leading to his laboratory, we see several NEC ad posters posted on the walls. One of them shows Chinese characters representing enormous values such as "兆(10^{12} =trillion), 京(10^{16}), 垓(10^{20}),...正(10^{40}) and 載(10^{44})" in a cubically superposed design, and another shows an illustration with the motif of "Rubin's Vase," which is a well-known optical illusion.

The former poster seems to convey the message that the quantum computer is capable of instantaneously factorizing a huge number by making use of the property of "superposition" of the quantum, and the latter poster seems to attempt to show an image of that "superposition." In other words, a state may be expressed just like the picture of the Rubin's Vase, in which one can see two aspects, either the profiles of two people facing each other or the silhouette of a vase, but cannot see one of these aspects if the other aspect is watched too much. This poster is not wrong as a pictorial explanation of the logic, but it is not at all a representation of the "quantum computer" itself.

A large number of books and websites offer explanations of the "quantum computer," but the hurdle to be cleared is quite high in order for us to comprehend a real image of it. As outsiders, we may even be frustrated by the fact that the basic concept of "superposition" (the state in which a single bit can be both 0 and 1) is hard to be understood intuitively. This concept is quite unlike those of classical physics. The "quantum," which is a minimum mass of energy like a photon or electron, can simultaneously feature both "particle-like properties" and "wave-like properties." So some people suggest that "superposition" can be understood more easily in terms of the principle of "interference" that belongs to "wave-like properties." This notion refers to the fact that, when interference is caused by waves passing through two slits, one can know the slit that the interference passed through only in terms of probability. Even when this figurative explanation makes us feel that we have understood something, we then have to cross another hurdle, which is another basic concept of "entanglement" in the case of two quanta being present.

Quantum dynamics has a history of about a century, while computer science has a history of little more than a half century. Furthermore, the history of the "quantum computer" is as short as two decades and has been led exclusively by physicists as a research subject. If a real thing is presented to us and its function is described, we believe that we should be able to grasp its image in more detail......

Dr. Tsai et al. are reported be achieving steady results that can help realizing such aspirations. Our expectations in interviewing an expert of the standing of Dr. Tsai were indeed great.

How NEC's quantum computer research was begun

"In the beginning, our research was not conscious of the 'quantum computer' at all." Dr. Tsai began his talk with unexpected words.

"I was originally a researcher of the Josephson device, a device that makes use of the tunnel effect of electrons in the superconducting state. My involvement was also influenced by a recently undertaken national project on the subject. This project can be regarded as having heralded "nanoelectronics". By the way, I was the first person to use this term at NEC, back in 1986, but it was rather criticized as being 'incomprehensible' and unpopular (laughter). The actual situation was so inadequate that we had difficulty in procuring even the requisite electron beam exposure for producing fine devices, but we had been aiming at a "single-electron transistor" with an ultra low current consumption. This transistor makes it possible to switch the output ON-OFF by moving only one electron, while currently available computers necessitate almost a million electrons to create an ON or OFF state (each bit). We started with fundamental research into this subject and accumulated results little by little."

A turning point came in the early 1990's. It was around that time that Principal Researcher Yasunobu Nakamura who worked in the same laboratory as Dr. Tsai joined NEC. When they checked the electronic properties of a transistor made using aluminum electrodes, they found that like the electron, scattered energy levels were featured, in spite of it being an electric circuit overall.

"From around 1995, we noticed this characteristic and started an experiment by applying microwaves to the circuit and checking the energy difference between the two lowest energy levels. It was just like the spectrometric experiment of applying light on an atom and checking the spectrum. Then, Dr. Nakamura contributed a paper on the results of this experiment to the journal Physical Review Letters. This research was actually the discovery of "quantum coherence," the phenomenon leading to the verification of the principles of the "quantum computer." However, we did not mention this because we were not yet at the stage of controlling the quantum state."

Meanwhile, it seems that NEC documents used for the domestic invitation of public application projects and in-house reports had started PR suggesting that the research would contribute to the quantum computer. This was a judgment of the research management team in consideration of world trends. Apart from this development, the research was gradually focused on the confirmation of the changes in time of the "superposition" states of quanta. The laboratory confirmed the behavior of the qubit (quantum bit) in solid devices for the first time in the world in November '98, and succeeded in creating "superposition"

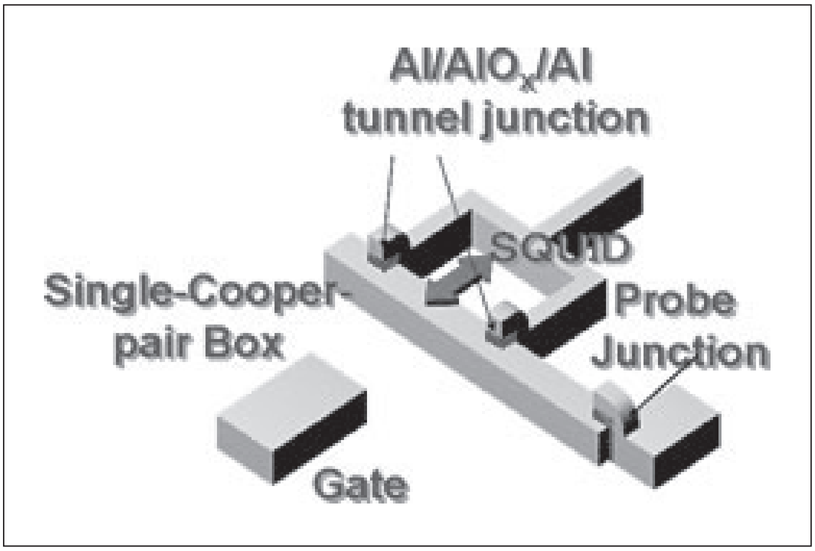


Fig. 1 The solid-state device consisted of aluminum thin film having a thickness of about 50 nanometers.

arbitrarily in '99 (**Fig. 1**). With regard to the above, the limitation "in solid devices" is added because major laboratories worldwide are currently competing in the production of the qubit, using their own individually developed methods. These include the use of ions in a vacuum, molecules in liquid and photons. The author has therefore adopted the method "in solid devices" with the view that it is the most advantageous method.

Photo 1 Dr. Tsai at his laboratory.

There are several hurdles to be crossed before practical implementation can be achieved

At this point, it may be necessary to offer a further explanation on the development of the "quantum computer." Since the world of quantum dynamics is a place in which the conventional wisdom of the macroscopic world does not work at all, understanding is difficult and we have to resort to multiple keywords. The bits (combination of <0> and <1>) that are the basis of the "classical computer," are in the "superposition" states with the qubits. When the "entanglement" state is created between the qubits to make them inseparable, a "quantum circuit" can be formed. This is the basic principle of quantum logic operations and can function as a universal gate playing the roles of AND, OR and NAND of traditional computers. The requirement at the device level is to enable these circuits to be controlled as desired.

"It was an important hurdle to create the 'entanglement' state between two qubits, but we succeeded in achieving it in February 2003 (**Fig. 2**). Since then, we have added improvements for the arbitrary control of qubits in order to enable logic operations and we have also

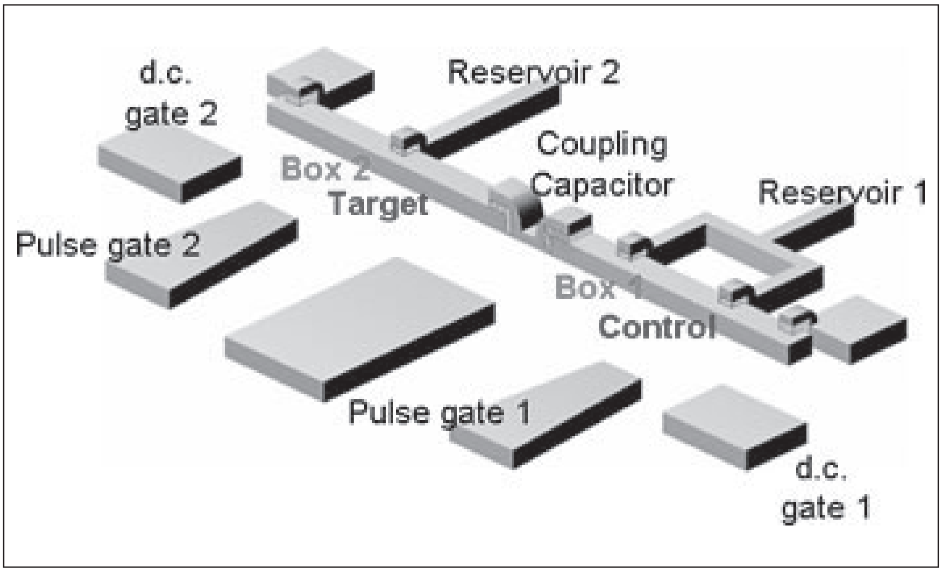


Fig. 2 Device structure used in the experiment, demonstrating the entangled state.

identified the conditions of the applied voltage pulses," says Dr. Tsai.

These achievements have led Dr. Tsai to win the 2004 Nishina Memorial Award and the Agilent Europhysics Prize.

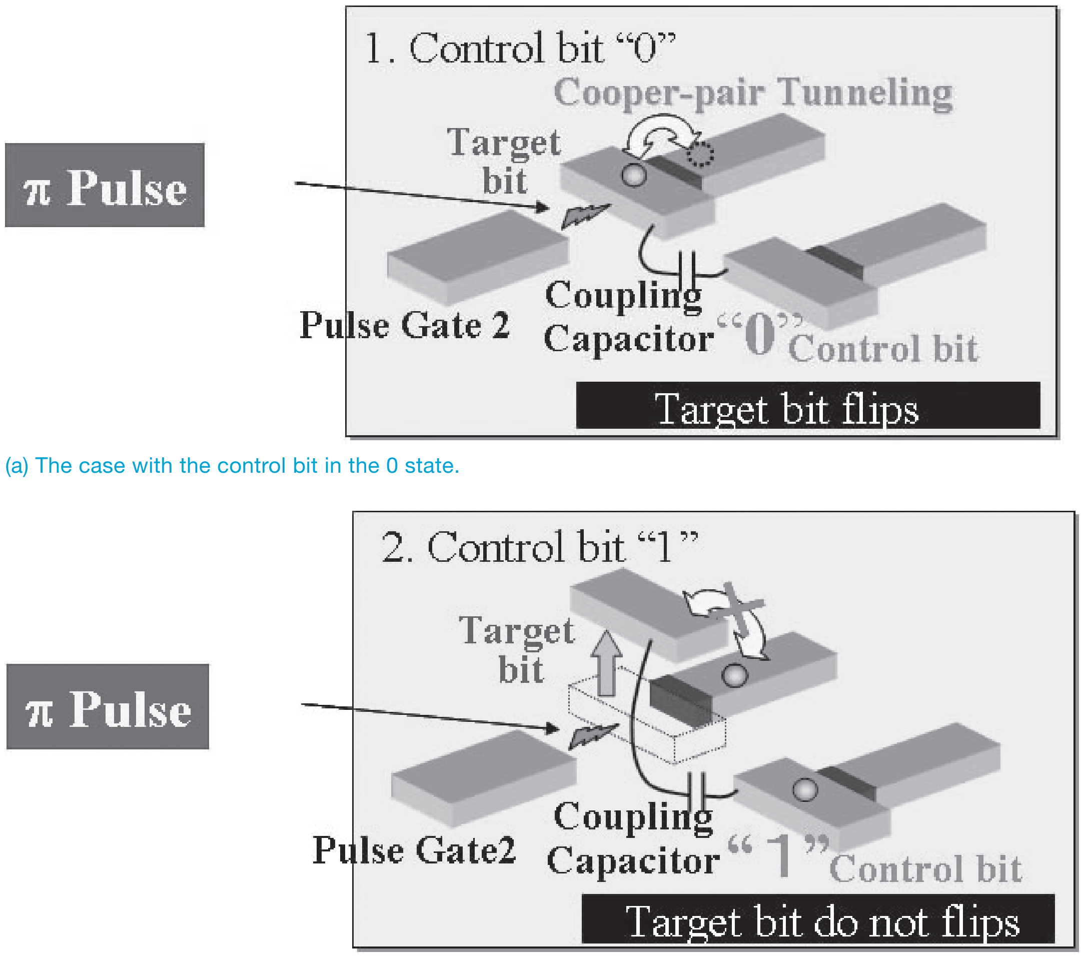
When we asked if the development of the "quantum computer" was at hand? The answer was "We cannot yet say so". "We cannot create in an instant, computers such as those that we are using today. First of all, we must enable the retention of the 'entanglement' state, free from environmental effects, as long as possible. We are still experimenting under strictly controlled cryogenic conditions. The next hurdle is to create a large number of qubits. With the quantum computer, an increase in the number of qubits can increase the 'entanglement' states to the order of the power of 2^N . It is possible to express 4 values with 2 qubits, 8 values with 3 qubits and, with 100 qubits, it is possible to express a number that is a million times a trillion multiplied by a trillion.... This can be considered equal to the computing capability of traditional computers. The reason that we selected the solid device was that we thought that the time would come in which a quantum computer containing many qubits would be required (**Fig. 3**)."

"We should also be advancing more important research....," continues Dr. Tsai.

"In the first place, research into the kinds of problems solved by the quantum computer and how they are solved is still inadequate. This is research into aspects of algorithms, programs and applications. Basically, the quantum computer is suitable for dealing with problems that are hard to be dealt with by conventional computers because of the need for one-by-one solutions, so algorithms are proposed for solving the problems of factorization and database inquiries. However, when factorization becomes a very simple problem for the quantum computer, the basis of the current communication encryption system based on the combination of prime numbers will no longer be adequate. Based on this perspective, applications in the field of information communication such as 'quantum encryption' are conceived, making use of the properties of quanta. NEC is also a leader in this field (see the article on page 254). It will be only after the weak points of the quantum computer are identified and the development of hardware is coupled with the study of software such as algorithms, that a practical quantum computer will be born."

Does this mean that it might take a hundred years as some people commonly assert?

"No, we have made considerable advancements, at least in the last five years. New knowledge and significant breakthroughs are also expected in the near future. So, I guess that a practical implementation will come in ten or twenty years. However, both appearance and applications may be quite different from the current computers. The result may not for example, take the form of a general-purpose computer."



(a) The case with the control bit in the 0 state.

(b) The case with the control bit in the 1 state.

Fig. 3 Mechanism of a logical operation on the device.

The art of laboratory leadership: "Encourage originality and adopt an open policy."

It is said that some of the quantum computer researchers of the past abandoned this subject because of the inherent difficulties. It is no wonder that such pessimism was aroused because this research is just like trekking in a forest of intelligence where intuition does not work. But there are still many people in the world who are tackling this difficult subject with young, optimistic minds. The laboratory of Dr. Tsai is a typical example. Outsiders like us cannot understand everything based on theory, but at least we can be encouraged by the brave endeavors of researchers such as Dr. Tsai.

The laboratory led by Dr. Tsai employs many talented researchers, who have achieved fame via the societies and research journals in this field. These include Dr. Tsuyoshi Yamamoto (who doubles as a RIKEN researcher), Dr. Yuri Pashkin (RIKEN researcher) and Dr. Oleg Astafiev (similarly employed) as well as Dr. Nakamura mentioned above. Their brilliant achievements in the field of the quantum computer are also the results of the teamwork of these variously talented researchers. We asked Dr. Tsai about the knack of leading such a talented team and achieving such fruitful results.

"No special method" he replied. "I leave them alone so that they are free to exhibit their originalities. To promote research effectively, it is important to have an environment in which people can stimulate each other by exchanging ideas in great variety. To be more open in searching for human resources may be an essential input for encouraging Japanese science and technology in general."

Dr. Tsai is Chinese from Taiwan. As his father was a diplomat, he spent the first half of his elementary school life in Japan. He came to know his wife who is Japanese when he was attending the State University of New York. His words, which are quoted above are backed by his own experiences in living in different cultural spheres in Taiwan, Japan and the United States, and also by the experience that he gained twenty years ago as the first non-Japanese researcher in NEC Corporation. He is also interested in the world of art, and his hobby is in the architectural design of houses. His plans for which are to earn a reputation for being "open, roomy and personal but at the same time, functional and easy to use." This seems to be rather similar to his strategy as a laboratory head. We are confident that we may expect much from his research results in the coming years.

(Interviewed/compiled by Haruhito Tsuchiya)

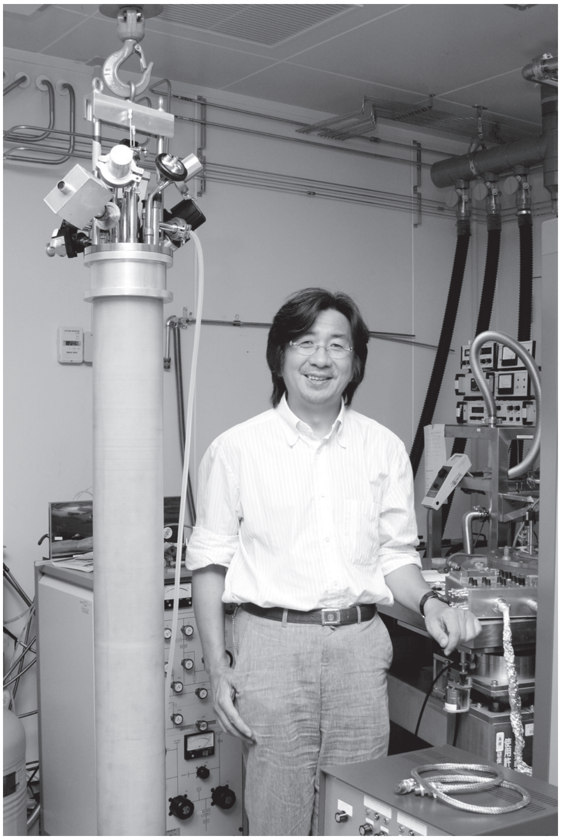


Photo 2 Quantum bit cooling device.