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Trends in the Research on Single Electron Electronics
— Is it possible to break through the limits of semiconductor integrated circuits? —

NOBUYUKI KOGUCHI (*Affiliated Fellow*) AND JUN-ICHIRO TAKANO
Materials and Manufacturing Technology Research Unit

5.1 Introduction

Semiconductor devices based on silicon and computers using these devices have drastically grown in accordance with Moore's Law. It is said, however, that these devices are approaching their limits due to device operation problems caused by miniaturization and heat evolution derived from the high degree of integration.

The Japan Science and Technology Corporation is now promoting basic research projects aiming at the creation of innovative technical seeds by establishing 13 research areas under the six strategic objectives that have been newly proposed by the government (Ministry of Education, Culture, Sports, Science and Technology) in fiscal 2002 as the "Strategy Creation Program." The total budget for these projects amounts to ¥4.4 billion. One of the six strategic objectives is the "creation of nano-devices, materials, and systems for breaking through the limits of integration and functions in information processing and communication technologies," and focused and intensive activities have been started.

Also, "Measures to promote the research and development of nano-technology and nano-materials" established by the Science and Technology Council in June 2002 points out the necessity to construct diversified device systems based on new principles that enable next generation information processing and communication. The proposal emphasizes the importance of research on devices systems, and integration technology based on a new principle that utilizes single electrons for operation instead of transistors that have been used for conventional integrated circuits.

If construction of integrated circuits using device systems that operate with single electrons are realized, power consumption will be reduced to a ten-thousandth to a hundred-thousandth of that required for conventional integrated circuits. It is also expected that the operating limits will be expanded, and that the malfunction problem of integrated circuits caused by the evolution of heat will be solved.

The device system that operates with single electrons functions based on a new operating principle called "coulomb blockade," which is inherent in single electrons. There are three major approaches for integration as follows:

(1) To break through the limits of integration by replacing the transistors that have been used for conventional integrated circuits with single electron transistors, following in the present system of the circuit architecture (aiming at realizing practical application within 10 years).
(2) To break through the limits of integration by changing the circuit architecture to a new structure called the "Binary Decision Diagrams," which is suited for operation using single electrons (aiming at realizing practical application within 10 to 15 years).
(3) To break through the limits of integration by adopting a new information processing method that does not use electrical wiring — a structure called "Quantum Cellular Automata," which utilizes single electrons

(aiming at realizing practical application later than item (2)).

This report summarizes the present situation and future prospect of research and development of such integrated circuits that function using single electrons.

5.2 Coulomb blockade Phenomenon

The operating principle of a device system that utilizes single electrons is based on a phenomenon called coulomb blockade. This phenomenon occurs when the size of materials such as metals and semiconductors is reduced.

When electrodes are connected to very small pieces of metals or semiconductor islands (called coulomb islands) through a gap on the order of nanometers (called a tunnel gap), electrons transfer to the coulomb islands by tunneling. When the islands of metals or semiconductors are large, the electrons can transfer freely; however, the motion of electrons is blocked if the islands are in the nanometer range. Nevertheless, the electrons can move if a certain level of voltage is applied to the electrodes. This phenomenon is called the "Coulomb Blockade phenomenon."

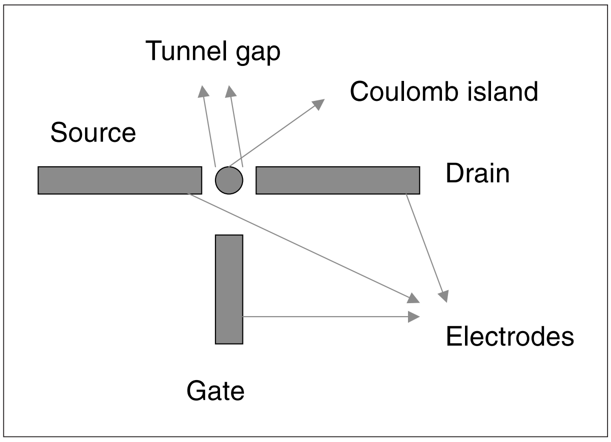
5.3 Integration of the single electron transistor

5.3.1 Single electron transistor

Conventional transistors operate based on currents consisting of one to a hundred thousand electrons. Single electron transistors, however, operate based on "one electron (single electron)" due to the Coulomb Blockade phenomenon. Figure 1 shows the structure of a single electron transistor. This transistor, like conventional transistors, consists of three electrodes — source, drain, and gate, but it differs from conventional transistors in that a fine Coulomb island is placed among the electrodes.

Regarding the single electron transistor, many studies are being undertaken all over the world, and there are diversified materials for the targets of the studies. In order to realize the practical application of the single electron transistor, it is

Figure 1: Single electron transistor



necessary to reduce the size of Coulomb islands to the order of nanometers so that the transistor can operate at room temperature. In the early stage of research, it was difficult to realize fine Coulomb islands and the transistor could operate only at low temperatures. However, the operation of single electron transistors at room temperature has now been confirmed using some kinds of metals and semiconductors.

5.3.2 Integration

While the single electron transistor is suited for high-density integration because its structure itself is essentially small, research on integration is still at the beginning stage.

As a future prospect of the single electron transistor, Professor Shunri Oda of Tokyo Institute of Technology commented as follows: "It is difficult to simply replace the devices that compose conventional integrated circuits made of silicon with single electron transistors. In integrated circuits that utilize single electron transistors, it is necessary to connect single electron transistors with miniature wiring, but miniature wiring in the nanometer-scale range is still difficult to fabricate. In addition, because the single electron transistor operates with single electrons, the output can drive only a limited number of single electron transistors in the next stage. In the future, therefore, research on hybrid circuits in which single electron transistors are formed on the silicon integrated circuit chip must be conducted in order to eliminate the necessity of constructing all circuits with only single electron transistors. For this reason, the materials used for single electron transistors must be compatible with the today's silicon process. It is very advantageous if silicon is used as the material for single electron transistors, because conventional integrated circuit production lines for integrated circuits made of silicon can be used with little modification.

Recently, Doctor Uchida et al. of Toshiba succeeded in fabricating hybrid circuits consisting of single electron transistors and conventional transistors on one silicon chip. Similar hybrid circuits have been fabricated by Doctor Igawa et al. of NTT. Furthermore, Doctor Yano's group of Hitachi manufactured trial silicon memories that operate with single electrons utilizing the coulomb blockade phenomenon.

A promising material other than silicon is carbon nanotubes. Doctor Kazuhiko Matsumoto's group of the National Institute of Advanced Industrial Science and Technology recently developed an integration technology for single electron transistors using carbon nanotubes. Carbon nanotubes also enable miniature wiring. This technology is expected to grow as a promising integration technology for single electron transistors.

5.4 Logic circuit based on binary decision diagrams

In conventional integrated circuits made of silicon, transistors are connected in series so that the actions of AND, OR, and NOT are executed as the functional architecture. This requires lengthy wiring and large electric currents.

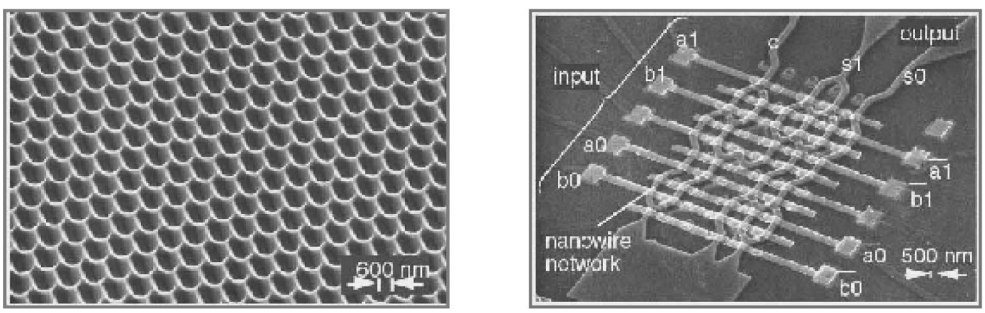
On the other hand, since the above-mentioned single electron transistor operates with single electrons, which correspond to a very small amount of electric current, the device is very sensitive to electric charges and tends to malfunction due to slight electrical changes in the environment. Therefore, it has been pointed out that the single electron transistor may not be suited for integration using conventional methods, as described in Chapter 5-3, so long as the conventional functional architecture is applied.

Therefore, to break through this limit for the integration of circuits, attempts to develop a functional architecture that is suited for operation by single electrons are being made with a different concept from the integration of single electron transistors. The new architecture being studied for integrated circuits that is suitable for operation by single electrons is based on "Binary Decision Diagrams."

It is expected that the logic circuits based on the Binary Decision Diagram will enable easier design of circuits. Since the basic action for constructing the logic circuits is a simple binary branching switch, various physical phenomena that enable switching over the transfer direction of signal media according to the input can be utilized for the construction of circuits. Above all, devices that operate with single electrons meet the requirements of high integration and low power consumption.

Figure 2 shows scanning electron microphotographs (taken by Professor Hideki Hasegawa's group of Hokkaido University) of an indium-gallium-arsenic (InGaAs) hexagonal quantum wire

Figure 2: InGaAs hexagonal quantum wire network formed on a fabricated substrate (left), and an integrated circuit based on binary decision diagrams (2-bit adding machine) using this technology.



Source: Web-site of Hasegawa Laboratory of Hokkaido University.
http://www.rciqe.hokudai.ac.jp/iede/2_naiyou_j.html

network formed on a micro-fabricated substrate in advance, and an integrated circuit based on Binary Decision Diagram (2-bit adder) that utilizes this technology.

In the integrated circuit based on Binary Decision Diagram, fine wires of nano-scale form a network of hexagonal meshes, and straight metallic microelectrodes are arranged in the network. The Y-shaped branches formed at the junctions of the nano-scale wires act as the switches for single electron transistors, and the switching action is controlled by the metallic electrodes. The logic circuit is constructed with these elements.

Professor Hasegawa, proponent of integrated circuit based on binary decision diagrams, commented as follows:

”This integrated circuit based on Binary Decision Diagram does not require a large electric current for operation because the functional architecture does not rely on the serial connection that is used for conventional integrated circuits in which the output of a transistor is used for the input to the next stage. It has also been found that this system requires less number of devices than the logic gate system to attain the same level of function. Furthermore, this system is suited for high-density integration because the problem of lengthy wiring is solved, since the structure is well regulated, the fine wire network serves as the wiring, and there are no source and drain electrodes.”

Professor Hasegawa considers that compound semiconductors are the most suitable materials for these circuits because the technology for fabricating the fine wire network structure is mature. However, not only compound semiconductors but also various materials can be applied to such circuit system, and he thinks that if silicon is used to form a fine wire network comparable to that made of compound semiconductors, it would be more practical because the present manufacturing lines for silicon integrated circuits can be used with little modification.

5.5 Quantum cellular automata

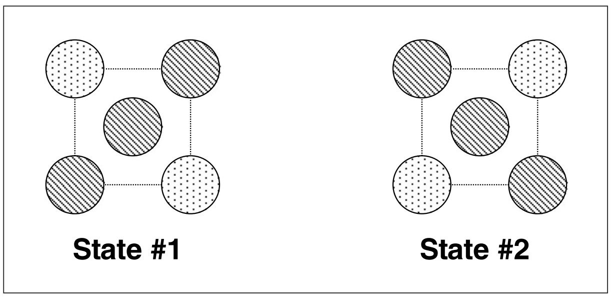
When the frontiers of integrated circuits based on single electron transistors and integration of the logic circuits based on binary decision diagrams are advanced, it is expected that the distance between single electron transistors interconnected with wiring and the size of the quantum wire networks will become less than 10 nm or smaller, making the tunnel effect of electrons prominent. When the tunnel effect becomes prominent, integrated circuits do not operate.

Cellular automata, particularly Quantum Cellular Automata (QCA), which operate by proximity interaction of single electrons without requiring lengthy wiring between devices, are expected to be effective for breaking through such limits.

Figure 3 shows cells consisting of five Coulomb islands (also called quantum dots) and two electrons.

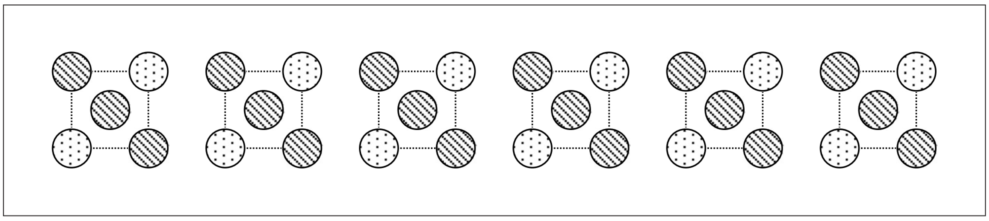
QCA functions with these cells as the operating unit. Since the total energy of a cell becomes lowest when the two electrons exist in the islands on the diagonal line declining to the left (State #1) or on the diagonal line declining to the right (State #2), electrons tend to take either of the two positions. When the direction of the alignment of two electrons in a cell is perpendicular to that of the two electrons in the adjacent cell (i.e., one cell is in State #1 and the other is in State #2), the electrons in the two cells repel each other so that they tend to align in parallel. When a number of cells are laid side by side as shown in Figure 4, electrons in all cells tend to take the same orientation in parallel. If the orientation of the electrons in the leftmost cell is reversed by 90 degrees by some means, the electrons in the

Figure 3: Schematic diagram of cells consisting of five coulomb islands.



Each of the dotted islands has one excessive electron, however the islands shaded with slanted lines do not have such excessive electrons. There are two states for stable distribution of the two electrons: on the diagonal line declining to the left (State #1), and on the diagonal line declining to the right (State #2). Tunneling occurs among the five coulomb islands.

Figure 4: Principle of cellular automata



When the cells are laid side by side, electrons in all cells tend to take parallel positions. Although static electric force acts on the electrons in the adjacent cell, tunneling of electrons does not occur.

adjacent cell tries to take the same orientation as the electrons in the leftmost cell.Thus, electrons in all cells try to take the same orientation, resulting in a domino effect. By combining many cells in this way, it becomes possible to transmit information from the leftmost cell to the cell on the opposite side without using wiring. It is now hoped that various logical operations necessary for computers can be executed by devising appropriate ways for cell arrangement.

The concept of QCA has just been introduced, and only experiments relating to its principle are being conducted. In order to realize QCA that operates at room temperature, it is necessary to develop a technology that enables the laying out of hyperfine structures such as quantum dots with good controllability making use of self-organization, etc. In addition to the so-called quantum dots of semiconductors, it has been recently proposed that a complex of ruthenium-based molecule having mixed valence, which has a much smaller structure than quantum dots, may realize QCA that operates at room temperature, and experiments are being conducted in the United States.

Doctor Tetsushi Tanamoto of LSI Laboratory of the Toshiba Research and Development Center, who conducted research on the simulated operation of QCA, commented about present status and future prospect as follows:

”QCA, devised by Lent et al. of Notre Dame University in the U.S., as an extremely miniature device, requires precise fabrication of quantum dots and accurate control of each electron. Although it is necessary to develop this method first, it will also become necessary in the future to develop various new types of Cellular Automata that are different from the QCA developed by Lent.”

Although the future of QCA is still uncertain, if it is realized, the device will operate with a very small amount of energy for controlling only one electron without suffering from the problems caused by wiring, and we will be able to drastically increase the degree of integration compared to conventional integrated circuits.

5.6 Status of research and development relating to single electron electronics in foreign countries

From Figure 5 to Figure 7 summarizes the results of investigation, using the ISI database of the U.S., into the number of papers related to single electrons among the total papers reported globally over the past 21 years (from January 1981 to October 2002). There were 1,934 papers in total that were retrieved using the keywords “Coulomb Blockade,” which is the operating principle of the new device system run by single electrons (Figure 5). Out of these, 631 papers were related to the single electron transistor (Figure 6). In order to search for papers oriented to the integration of single electron devices, the combination of keywords, “single electron” and “logic” or “memory” or “integrated” was used and 345 papers were retrieved (Figure 7-c). Furthermore, there were 11 papers relating to logic circuits based on the binary decision diagrams, and 81 papers relating to quantum-dot cellular automata (Figure 7-d).

As can be seen from these figures, the number of Japanese reports relating to “coulomb blockade” and “single electron transistor” is outstanding together with the U.S. and Germany. Particularly, application-oriented research aiming at integration is most actively conducted in Japan.

As not much time has passed since Professor Hasegawa et al. of Hokkaido University proposed

Figure 5: Results of retrieval using with "coulomb blockade" as the keywords.The total number of papers since 1986 was 1,934 (including 464 Japanese papers). No paper was retrieved from any country for 1985 or earlier.

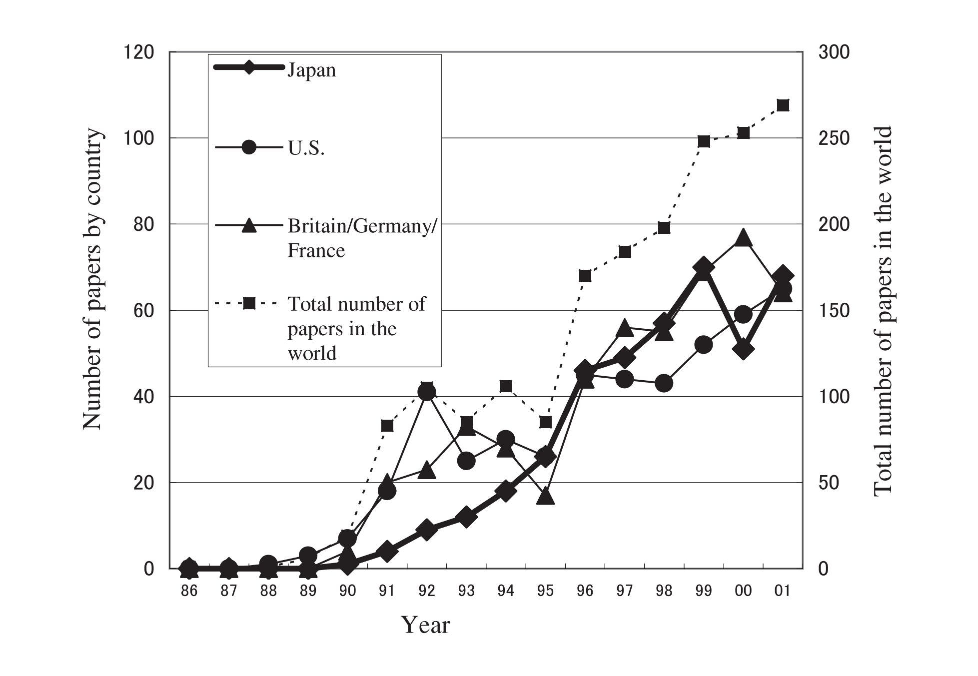
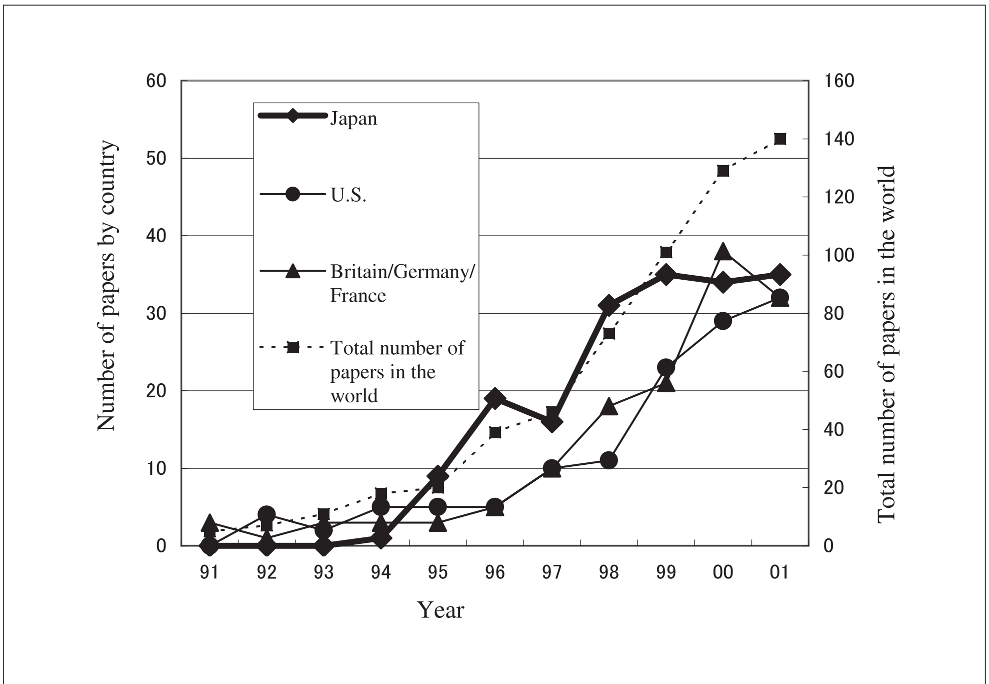


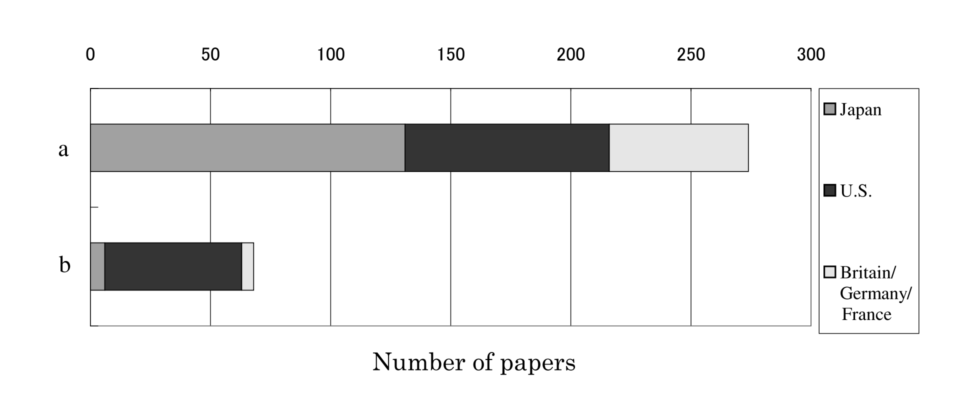
Figure 6: Results of retrieval with "single electron transistor" as the keywords.The total number of papers since 1991 was 631 (including 205 Japanese papers). No paper was retrieved from any country for 1990 or earlier.



the "logic circuit based on the binary decision diagrams," most of the papers on this subject have been reported by the Hokkaido University group. However, as this method is expected to be applied to a wide range of materials including silicon, research activities will expand in the future.

The number of papers published in the U.S. relating to quantum cellular automata (QCA) is predominant. QCA was originally proposed by C. S. Lent et al. of Notre Dame University of the U.S., and research works are being actively carried out in the United States primarily by researchers at the university. No experimental research work has been conducted in Japan relating to QCA,

Figure 7: (a) Result of retrieval with "single electron" and ("logic" or "memory" or "integrated") as the keywords, (b) results of retrieval with "quantum-dot automata" or ("quantum cellular automata" and "dot") or "quantum-dot cells" or ("cellular automaton" and "single electron") as the keywords.



(a) The total number of papers since 1991 was 345 (including 138 Japanese papers). No paper was retrieved from any country for 1990 or earlier. (b) The total number of papers since 1993 was 81 (including 6 Japanese papers).

although some simulated operation works have been carried out.

5.7 Conclusion

Present status and future prospect of research and development oriented to integrated circuits that operate with single electrons among devices supporting next generation information processing and communication are summarized.

Studies oriented to the integration of single electron devices are more actively carried out in Japan compared to any other country in the world. Regarding the logic circuits based on Binary Decision Diagrams, research works are now getting started primarily in Japan. As for Quantum Cellular Automata (QCA), research works are being actively carried out in the United States, whereas no experimental research work related to QCA has been conducted in Japan, although some works on the simulation have been done.

The prospect of QCA is still ambiguous, but since it will drastically increase the degree of integration once it is realized, Japan will be left far behind the U.S. unless we start some kind of research now.

For research on the establishment of device systems based on new principles such as "single electron electronics," it is necessary to provide more enhanced research resources, invested continuously from a long-term point of view, in addition to the "Strategy Creation Program" sponsored by the Japan Science and Technology Corporation.

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