Research Toward Nanoelectronic Computing Technologies in Japan

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Abstract

A perspective of the research activities in Japan aimed at the development of new computing technologies based on structures with ultra-small dimensions is presented. Examples are given of work toward the development of resonant tunneling circuits, electron-wave interference & single-electron tunneling devices, and atomic scale fabrication technologies.

1: Introduction

The search for circuitry which is not bound by the limits of conventional technologies has lead to research on a variety of radically different approaches to future electronics. The basic idea behind this work is to exploit physical effects in structures that are ultra small (nanometer size) in one or more dimensions. Quantum-effects such as resonant tunneling are being used in heterostructures with small vertical dimensions while electron-wave interference, single-electron tunneling, and other effects are being explored in nanostructures with small lateral dimensions.

Japan has been active in these areas for some time and has a wide range of current programs and long-term commitments in this exploration. In addition to internal funding within many industrial laboratories, support for these programs comes from a number of governmental sources, as indicated in Fig. 1.

Early university programs include the Sakaki Quantum Wave Project, which involved an average of 15 researchers over a period of 5 years, and the Project on Mesoscopic Electronics headed by Prof. T. Ikoma, which provided a unique joint program involving four universities and ten companies. University research activities have increased and a wide variety of university programs are currently underway.

Projects at six industrial laboratories are supported under the 10-year Quantum Functional Devices Project,[1] now in its third year. Within this project, each company is pursuing research along distinct lines with the overall goal of establishing basic technologies using controlled quantum effects in nanostructures for information processing systems in the 21st century.

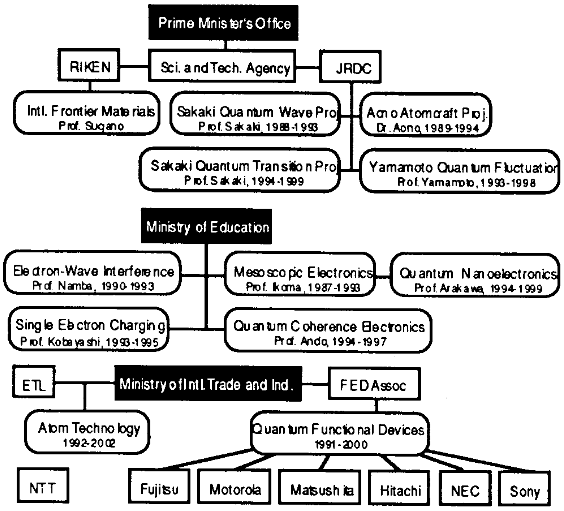

Fig. 1 - Japanese programs in nanostructure and quantum-effect electronics (partial listing).

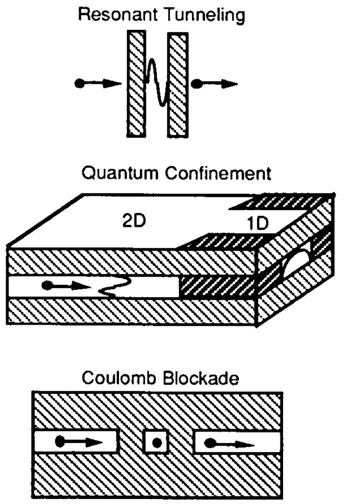

Fig. 2 - Physical effects in nanostructures.

Significant programs also exist at NTT and at national laboratories such as ETL and RIKEN. In addition, intensive joint research activities involving researchers from univeristies, industry, and national laboratories are being carried out on the most leading edge technologies. An example is the Atom Technology Project[2] in Tsukuba. This project ultimately aims at the manipulation of atoms and molecules as the basis of a future electronics technology, began just last year and will continue for a period of ten years.

In the remainer of this paper, I will describe some specific examples which illustrate the scope of this work and mention some general trends in these activities.

2: Exploiting Nanostructures

The ultra-small dimensions in nanostructures bring about a variety of physical effects which can possibly form the basis of a nanoelectronics technology. Several of these are illustrated in Fig. 2. The resonant tunneling (RT) effect is caused by electron-wave interference produced by thin potential barriers in, for example, a double barrier heterostructure. This effect produces a negative resistance characteristic which can be exploited in diodes or transistors. Quantum confinement effects, which already occur to some extent in the two-dimensional channel of a conventional MOSFET, are enhanced by the small size of nanostructures and the ability to confine electrons in more dimensions to produce one-dimensional "quantum wires" or zero-dimensional "quantum dots". The large separation in energy levels and the capability for exciting a single electron-wave mode leads to electronic behavior that can be exploited in devices. A third important physical effect in ultra-small structures is Coulomb blockade. This effect is related to the large change in Coulombic energy involved in the tunnelling of even a single electron between ultra-small regions and gives rise to correlated single electron tunneling (SET). SET leads to new possibilities for obtaining transistor-like operation and memory effects in extremely small structures.

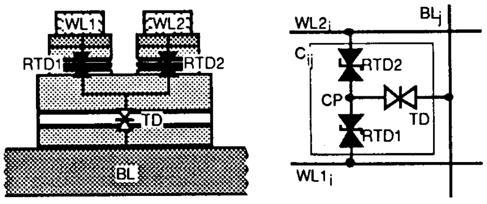

Fig. 3- Double-emitter resonant-tunneling SRAM cell array. (Courtesy of T. Mori, Fujitsu Labs. Work supported by NEDO).

Quantum-effect electronics based on resonant tunneling has reached the most advanced stage in terms of actual circuit demonstrations. Functional operation of SRAM cell arrays based on the double-emitter resonant demonstrated. This approach is of interest because of its scalability and its promise for realizing Gigabit memory chips. Weighted-sum threshold logic gates based on gated RT diodes also have been demonstrated[3] and are of potential use in neural networks and new computer architectures[4].

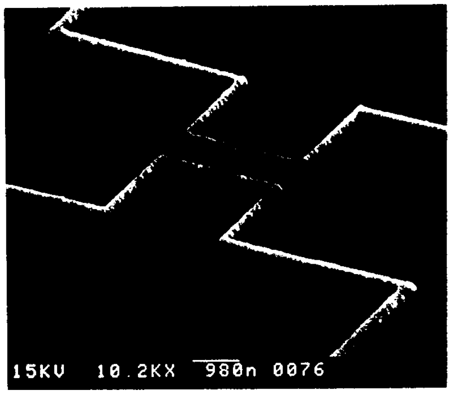

Fig. 4 - Quantum point-contact electron-wave injector & reflector structure (courtesy of M. Saito, Fujitsu Labs)

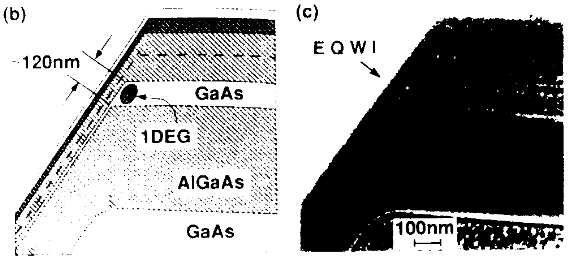

Fig. 5 - Quantum wire fabricated on a patterned facet plane (from Nakamura et al., 1993).

Although still far from actual circuitry, other new quantum-effect switching concepts which use negative resistance or negative transconductance effects are under investigation. One approach is the resonant scattering transistor,[5] in which gate-controlled resonant-tunneling between quantum-wells having different scattering rates serves to modulate the drain current. Negative transconductance is an interesting feature of this device and has been demonstrated experimentally.

A number of device concepts based on quantum-interference in quantum wires have been proposed and a few preliminary demonstrations of such concepts have been made. For example, quantum-interference in a structure representing the electron-wave analog of a microwave stub tuner has been reported.[6] However, most of the work on quantum wires and other low dimensional structures thus far has been concerned with basic physics and fabrication methods rather than device concepts. The study of basic physics has been possible in structures based on the controlled lateral confinement of electrons in a modulation doped heterostructure by fine-line surface electrodes, as illustrated in Fig. 4. This figure shows a simple structure for investigating the coupling between a quantum point contact injector and one-dimensional quantum wire states.[7] The high confinement potentials needed for enhanced quantization effects can not be obtained in such structures due to the weak lateral confinement. Hence, work on quantum wire structures in which electrons are highly confined by heterojunctions in both the vertical and lateral dimensions, such as the quantum wires fabricated on patterned facets[8] shown in Fig. 5, is being carried out and may lead to a technology suitable for circuitry.

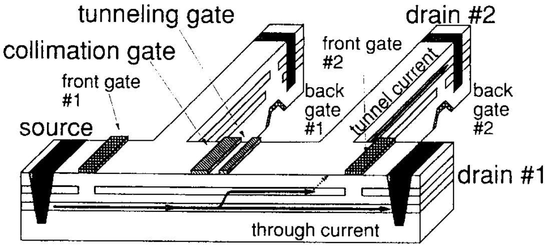

Fig. 6 - Distributed resonant coupling electron-wave switch (Courtesy of T. Ikoma, Univ. Tokyo)

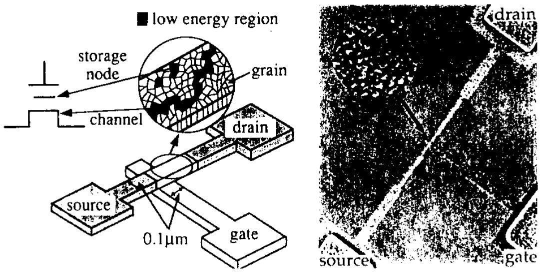

Fig. 7 - Fine grain polysilicon channel FET (Courtesy of K. Yano, Hitachi)

Basic limitations in the use of quantum-interference effects have recently lead to some shift in activity toward other device possibilities. For example, the limitation of extremely low current drive inherent in single-mode quantum wire structures is circumvented in the electron-wave switch shown in Fig. 6 by using distributed resonant coupling to switch collimated electrons between two-dimensional electron channels.[9] Partial collimation is obtained by the influence of an electrostatic potential on the ballistic electrons, which bends the electron paths in a manner analogous optical diffraction. A control gate switches electrons between channels not by depleting electrons but by only changing the electron-wave propagation path. Hence, high speed and low power dissipation is anticipated for this type of switch.

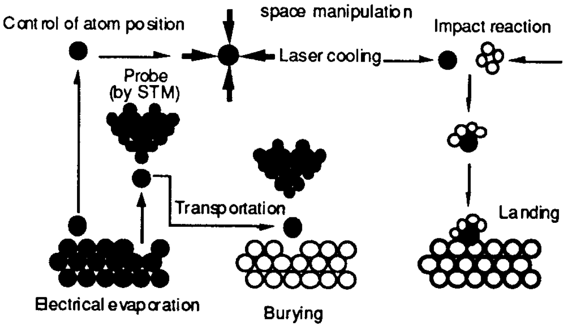

Fig. 8 - Atomic-molecular manipulation technology (courtesy of K. Tanaka, NAIR)

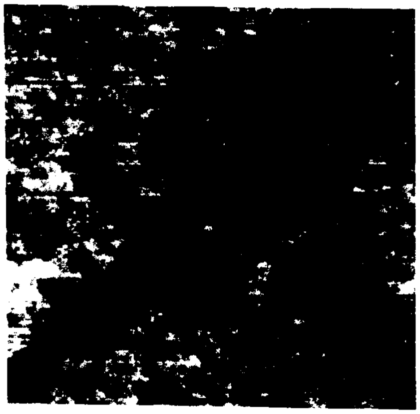

Fig. 9 - Nanometer scale patterns drawn on a silicon surface using scanning tunneling probe technology.

Interest in devices based on single-electron tunneling or Coulomb blockade effects has been increasing rapidly in Japan over the last year. One reason for this is the promise SET circuits hold for operation at higher temperatures. A memory effect at room temperature attributed to the storage of single electrons has been reported for ultra-thin channel poly-silicon FET's.[10] Quantized threshold shifts observed in the characteristics of this device and are thought to be caused by the storage of single electrons on a small poly-silicon grain, as illustrated in Fig. 7.

Some of the most forward looking research in Japan is aimed at developing future fabrication technologies for ultra-small structures, including techniques for manipulating individual atoms and molecules. Work on various aspects of this technology, such as the scanning probe manipulation technology depicted in Fig. 8, is being carried out at various laboratories. An example of the potential of this technology is given in Figure 9 which shows nanometer-scale patterns drawn on a silicon surface by extracting atoms using the tungsten tip of a scanning tunneling microscope.[11]

3: Conclusion

In summary, a broad range of work aimed at exploring the possibility of developing new computing technologies based on physical effects in devices with ultra-small dimensions is being carried out in Japan. Functional operation of resonant-tunneling digital circuits has already been demonstrated. Significant progress is being made in the fabrication and physical understanding of ultra-small nanostructures, and interesting device concepts are beginning to emerge. The ability to manipulate individual atoms and molecules could lead to the ultimate circuit technology of the future, and long-term projects in this area have now begun.

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