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A Proposal of Nano Scale Atom Switching Device

Yasuo Wada, Tsuyoshi Uda, Mark Lutwyche and Seiichi Kondo

Advanced Research Laboratory, Hitachi, Ltd.
2520 Akanuma Hatoyama, Saitama 350-03, Japan

A nano scale switching device, Atom Relay Transistor (ART) is proposed, which consists of atom wire, switching gate and switching atom, and operates based on the mechanical movement of the switching atom. The switching characteristics are simulated, and confirms acceptable characteristics of ART for digital applications. Dynamic operation circuit based on the ART concept is proposed, and the feasibility of dynamic random access memory is demonstrated. Logic circuits as NAND and NOR gates are also proposed. These circuit diagrams would enable an integration of 10^9 bit memory and 10^7 gate logic circuit on an approximately 200 μm square area, and would realize a super-computer operable at more than 10^{13} Hz.

1. Introduction

Advances in silicon integrated circuit technology are physically limited to further microminiaturization beyond the 100 nm level [1]. Therefore, new nano scale devices have recently been attracting attention as candidates to supersede silicon MOS transistors as the devices to be utilized in future integrated circuits [2]. The integrated circuit devices should fulfill the following requirements for high speed operation, dense integration and high performance. They are, (a) Input and output (I/O) signal balance, (b) I/O signal isolation, (c) integration capability, (d) high speed switching and (e) fabricability. This paper proposes very small atom size switching device, Atom Relay Transistor (ART), with dimensions below 10 nm, which would fulfill all these requirements. The basic operation, the possibility of the realization and superior characteristic proved by simulation are demonstrated.

2. Concept of atom wire

Figure 1 demonstrates the concept of atom wire, in which atoms are represented by circles and are arranged in a row. The atom wire structures include (A) simple structure, (B) periodic structure and (C) hexagonal structure. In addition, such structures as random structure and multiple line structures can be included in the atom wire configuration. Three dimensional structure is also possible, in which the atom wire consists of molecules such as fullerenes. These structures were energetically stable as ascertained also by the simulation based on the first order principle [3].

3. Atom Relay Transistor, ART

The basic concept of Atom Relay Transistor, ART, is schematically depicted in Fig. 2 in plan view, in which an individual atom is also represented by a circle. ART consists of an atom wire, a switching atom, a switching gate and a reset gate. The atom wire is conductive when the switching atom is set in the atom wire, while it is non-conductive when the switching atom is

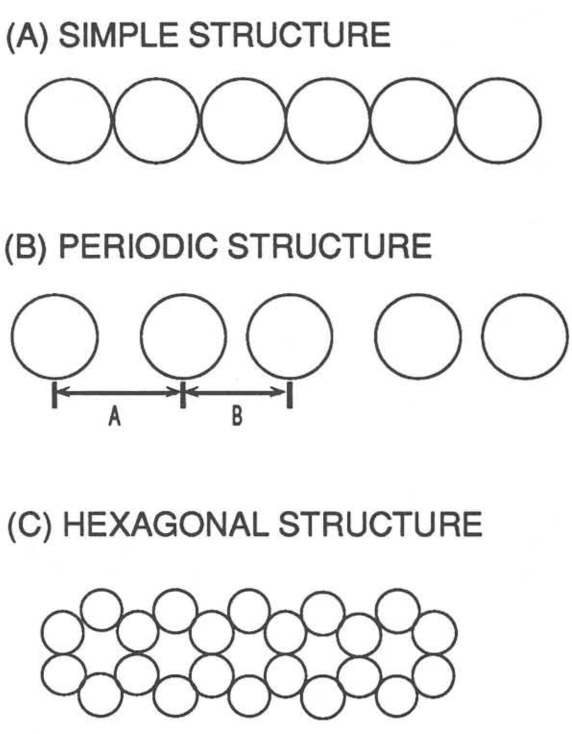

Figure 1 Examples of atom wire structures

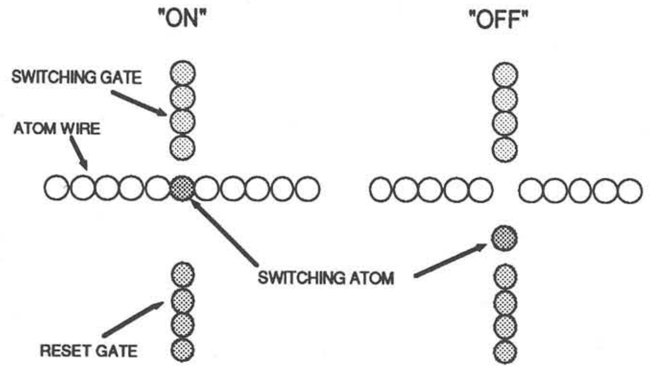

Figure 2 Basic configuration of Atom Relay Transistor, ART

removed from the atom wire by the electric field supplied from the switching gate. The switching characteristics of ART were simulated by the tight binding method and the results are shown in Fig. 3 (a) and (b). It is clearly shown that a electron travels through the atom wire consisting of 30 atoms with a separation of 0.2 nm, under an electric field of 3 x 10^5 V/cm, at a velocity of about 10^8 cm/s (left). On the other hand, it is almost completely cut if a 0.4 nm gap is formed in the atom wire (right). The figure also depicts that the electron density becomes higher at the end of atom wire, which corresponds to about 100 mV and can move the switching atom in the next ART. Thus the requirement for (a) I/O balance is fulfilled in ART. Since the ART configuration has three terminals, the second requirement, (b) I/O signal isolation is also achieved. The reset gate puts the switching atom back to the original state by applying a reset pulse, which makes possible the synchronous operation of the whole circuit.

4. Memory and logic circuits

The Atom Relay Transistor can also offer a dynamic operation by using a self-relay configuration. The structure is schematically shown in Fig. 4 in plan view, where the switching atom is removed from the atom wire by the electric field from the atom wire itself. The simulation results confirmed that the switching atom is removed from the atom wire, and that the electron is trapped in the atom loop. Dynamic memory cell is made possible, which uses an area of only about 10^3 atoms, and 10^9 bit occupies only about 200 μm square. Thus the third requirement, (c) integration capability is fulfilled by ART.

The switching frequency of ART can be on the order of 10^{14} Hz, because the intrinsic vibration frequency of an atom is more than the order of 10^{14} Hz [4]. The electric field from the switching gate can also move the switching atom within this time duration. Therefore, the forth requirement, (d) high speed operation is fulfilled.

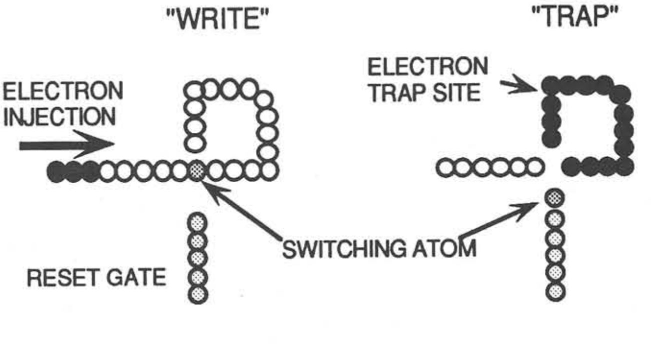

Figure 4 Schematic figure of a self-relay configuration: "write" (left) and "trap" (right) states.

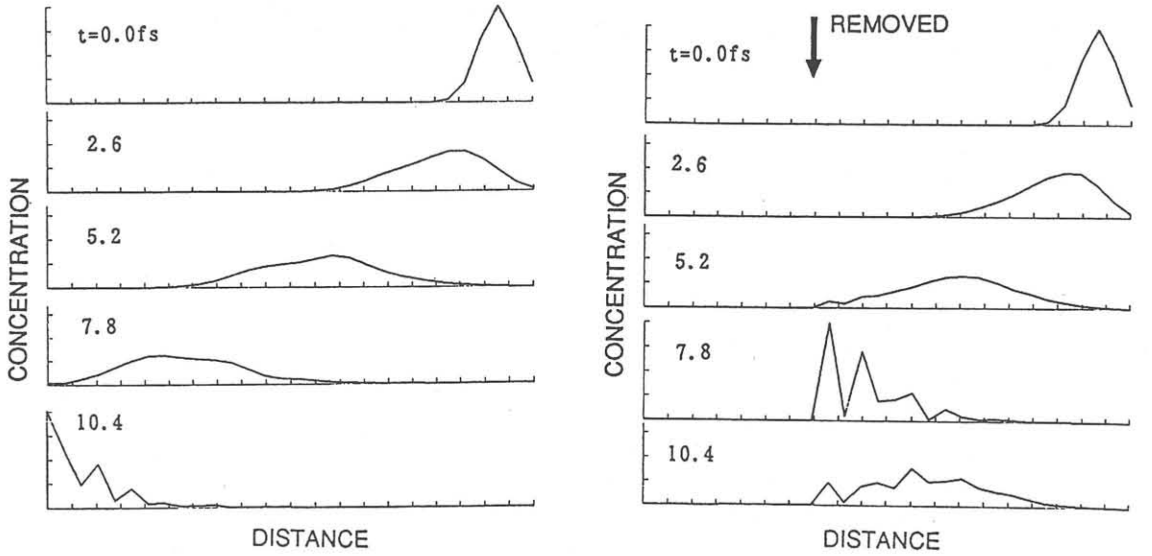

Figure 3 Simulation results of switching characteristics of the Atom Relay Transistor : "on" state (left) and "off" state (right)

Logic circuits such as NAND and NOR gates can also be realized by the ART, and a rule of thumb estimation of the area occupied by a 10^7 gate logic circuit measures 20 µm square. Therefore, the chip area of a supercomputer consisting of a 10^9 bit memory and a 10^7 gate logic circuit measures about 200 µm square. Even the longest signal delay on the chip is in the order of 10^{-13} s, which would make it possible to realize a 10^{13} Hz operation computer.

5. Fabricability

The last and most important problem is (e) fabricability, which is also a limitation for the present integrated circuit technology. Atom manipulation technology demonstrated in ref. [5] would make possible the construction of the ART structure, however, it would take too much time to fully fabricate the integrated circuits consisting of more than 10^{10} atoms by STM technology. One of the solutions would be to utilize the self-organization technology as reported in ref. [6], where barium atoms align on the tungsten surface in a self-assembled manner. Therefore, only a fraction of the atoms have to be moved to configure the ART structure. Still, highly concentrated endeavor to develop the atomic manipulation technology should be necessary to realize the Atom Relay Transistor.

6. Comparison with other candidate devices - concluding remarks

The candidate nano scale devices were evaluated with the above mentioned five requirements. The reason why the MOS transistor has been utilized in integrated circuit is that it almost ideally fulfills all the requirements, as shown in Table 1. These devices are also examined quantitatively in terms of speed and integration capability, as shown in Fig. 5, along with the historical switching devices. These results indicate that the Atom Relay Transistor exhibits superior characteristics to the other devices, and is the most promising candidate for the future integrated circuit device.

acknowledgments

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Table 1 Evaluation of the Candidate Superceding Devices Based on the Characteristics Necessary for the Future Integrated Circuit

	MOS FET	QUANTUM DEVICE	SET	MOLECULAR DEVICE	ATOM SWITCH
I/O BALANCE	○	△	○	△	○
I/O ISOLATION	○	○	○	△	○
SPEED	○	◎	◎	△	◎
INTEG-RATION	○	○	○	◎	◎
FABRI-CABILITY	○	△	△	△	△

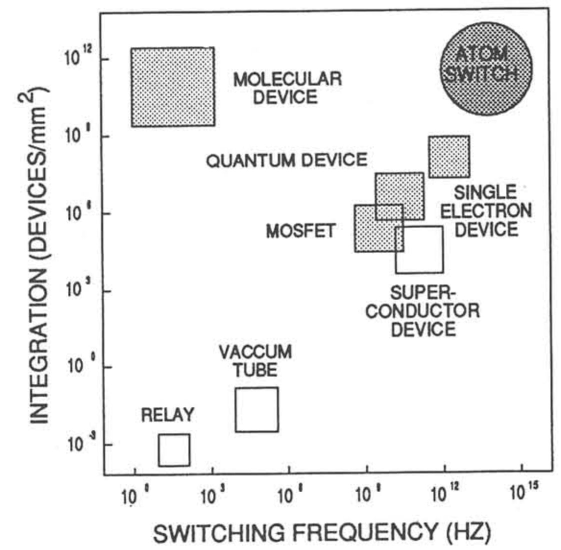

Figure 5 Evaluation of the candidate devices based on speed and integration capability

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