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Turnstile Based Single-Electron Logic Devices

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1. Introduction

Present-day semiconductor devices have to rely on operating principles based on the average behaviour of many electrons. When the number of electrons is reduced to less than 1,000, fluctuations in electron number become relatively large, and we cannot distinguish between a '0' and a '1' with the required certainty. If we can control individual electrons, instead of only the average behaviour of many electrons, we can operate with precise numbers and eventually with one electron. In the single-electron devices in which one bit of information is represented by a few electrons, the power consumption can be drastically reduced.

In single-electron logic circuits, the electron transfer between two electron states is controlled instead of the electron distribution. Such electron transfer can be realised by turnstile device [1] which has been applied to single-electron switch for the flow control of binary information [2]. Using single-electron switch, phase-locked single-electron logic [2], single-electron cellular automata [3], and single-electron binary decision diagram (BDD) logic [4], were proposed. This paper describes the experimental status.

2. Multiple-tunnel junction (MTJ)

An important element for single-electron devices is MTJ in which a series of small islands is formed. The charging energy of the island creates an energy barrier which blocks the entrance of electrons into the MTJ so that multi-stable states of different numbers of electrons can be formed. The MTJ is also important in suppressing offset-charge and co-tunnelling effects. To realise very small MTJ structures, we have used a side-gated structure in δ-doped GaAs. [5] Potential fluctuations in the δ-doped layer create several small islands in a constriction without the need for lithography to define the individual islands. The Fermi energy of the electrons in the constriction could be modified by biasing the side-gate.

Turnstile device was constructed using δ-doped GaAs MTJs. As shown in Fig. 1, the linear dependence of gate frequency f and amplitude on direct current, $I = nef$, was obtained, where n is the number of transferred electrons per cycle.

3. Single-electron BDD logic

Binary decision diagram (BDD) [6, 7] is now commonly used to construct LSIs. The CMOS pass-transistor logic circuits based on BDD architecture have several merits compared to the usual AND/OR combinational circuits; higher packing density, lower power consumption, and higher speed.

A BDD represents a digital function as a directed acylic graph with each node labelled by a variable. As an example, consider the three-variable digital function represented by the Boolean equation, $(X_1+X_2)X_3$. This function can be represented by the BDD in Fig. 2(a). A BDD is a graph composed of many nodes and two leaves; in the figure each node is represented by a circle containing the variable X_1, X_2, X_3 with two branches labelled 0 and 1, and a leaf is represented by a square containing the value "0" or "1". In determining the value of the function, we enter at the root and proceed downward to a leaf. At each node, we follow the branch corresponding to the value of the variable; that is, we follow the branch labelled 0 if X_i=0 and 1 if X_i=1. For a given set of variables there is only one path from the root to a leaf of "0" or "1." The value of the function is equal to the value of the leaf at the end of the path. A BDD is composed of many identical interconnected nodes, so the node is the unit element of a BDD. Each of the elements receives single-electrons from a preceding element through one of the entry branches, and then sends them to a following device through the exit branch corresponding to the binary value of the input. This operation is simple two-way switching.

4. Single-electron two-way switch device

Single-electron two-way switch device, based on the modulation of Coulomb blockade regions, was proposed and demonstrated. [8] The switch consists of three MTJs as shown in Fig. 3, and a turnstile current I flows through the top MTJ and one of the bottom two MTJs, I_1 or I_2 (Fig. 4). The switching characteristics were obtained by changing side-gate voltages V, where a rf signal from 0.5 to 6 MHz was applied to the control gate. In this experiment, around sixty electrons are carried by one modulation cycle of V_{rf}.

5. Multi-clocking scheme

For the construction of logic devices in BDD architecture, a multi-clocking scheme can be adopted to overcome the problem of series connection. Example of logic function $(X_1+X_2)X_3$ is shown in Fig. 2(b), where clocking signals, ϕ_1,.., ϕ_4, are applied through capacitors.

In a device with two nodes connected in series (Fig. 5(a)), we measured turnstile current as a function of phase delay between two voltage pulses on the gates. Three MTJs (MTJ1 - MTJ3) which form two nodes are set in the Coulomb blockade regimes by applying negative voltages to the side-gates (G_1-G_3). When two trapezoidal voltage pulses are applied on two gates (G_{rf1} and G_{rf2}), electrical potentials of the each node are changed and electrons are carried. The turnstile current was measured under zero-bias voltage and under sequential two trapezoidal voltage pulses with phase delay (Δt). When the two synchronised pulses were applied on the gates, that is, Δt = 0, the turnstile current was not observed. When a backward tail of pulse to G_{rf1} just overlaps a forward tail to G_{rf2} as shown in an inset of Fig. 5(b), a maximum turnstile current flows in the circuit. This shows that the amplitude of turnstile current strongly depends on the delay of the second wave.

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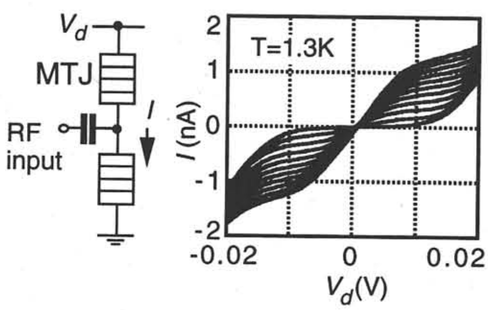
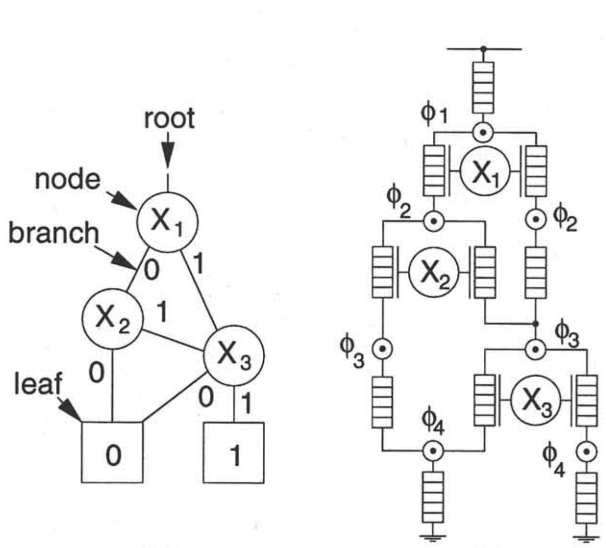


Fig. 1 Measured turnstile currents at gate frequencies from 10 MHz to 1 MHz at 1 MHz intervals and without an RF input.



(a) (b)

Fig. 2 (a) A BDD graph for a digital function $(X_1+X_2)X_3$.
(b) Implementation of single-electron BDD logic device by multi-clocking scheme.

RF

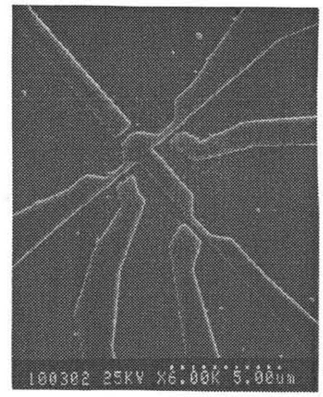
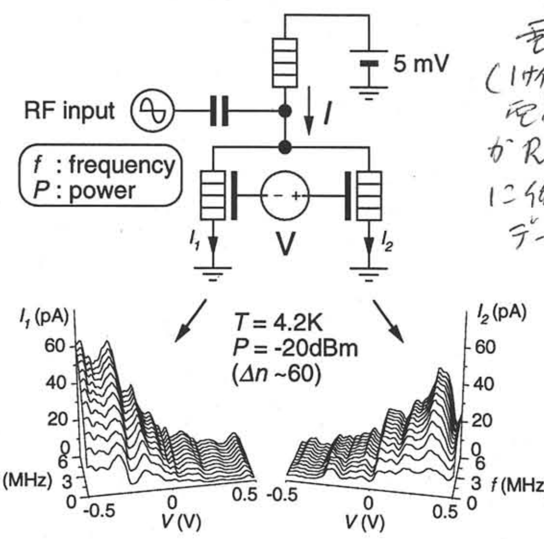
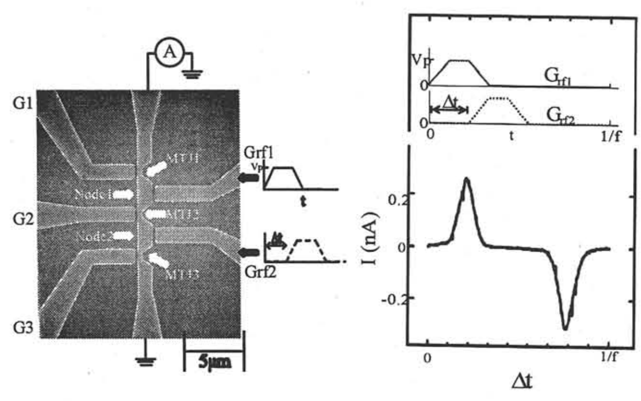


Fig. 3 Scanning electron micrograph of a single-electron two-way switch device.



電流(1サイクルの電子数)がRFパワーに依存するデータ.

Fig. 4 Equivalent circuit of Fig. 3, and measured frequency dependence of the two-way switching characteristic.



(a) (b)

Fig. 5 (a) Scanning electron micrograph of a device with a series connection of two nodes (Node1 and Node2). (b) Turnstile current characteristics with phase delay (Δt). One cycle of phase delay in the sequential modulation is derived. Inset shows an example of time delay of two trapezoidal pulses. Frequency is 0.5 MHz with voltage 0.5 V.