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Multiple-Valued Logic Devices Using Single-Electron Circuits

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One of the challenges in microelectronics is the development of novel electronic devices that can perform functional computing by utilizing inherent properties of quantum phenomena. We have developed one such computation device: *a multiple-valued logic device using single-electron circuits.*

The multiple-valued logic is a way of implementing digital operations by using a multiple set of logical values {0, 1, 2, 3, ...} instead of a binary set {0, 1}. The logic process of the multiple-valued logic is much more sophisticated than that of the binary logic, so the multiple-valued logic is expected to be more powerful for implementing digital functions with a smaller number of devices. But in practice, it has been unsuccessful to construct multiple-valued logic LSIs because most of elemental functions of the multiple-valued logic are hard to implement using the CMOS circuit. For example, the staircase transfer function such as illustrated in Fig. 1, which is usually required in multiple-valued logics, cannnot be implemented concisely on a CMOS circuit.

To overcome this problem, we here propose an idea that multiple-valued logic systems can be constructed with a compact circuit by using the single-electron circuit technology. The single-electron circuit is a quantum electronic circuit based on the Coulomb blockade effect in electron tunneling. A conspicuous property of the single-electron circuit is that the circuit shows "quantized behavior" in its operation. This quantization is caused by the fact that the charge on each node of the single-electron circuit is changed only through electron tunnelings. Because one electron is transferred through a tunneling event, the variation of the node charge is necessarily quantized in units of the elementary charge. In consequence, the output voltage changes as a discontinuous function of the input voltage.

To present practical form of this idea, we developed the circuit structure for elemental multiple-valued logic gates, using single-electron circuits. For an instance, we present in Fig. 2 a sample circuit that produces the staircase transfer function. The circuit consists of only four tunnel junctions and five capacitors. By designing the circuit parameters, we can control the number of steps in the transfer function. If we must implement the same function on a CMOS circuit, a comparator array combined with a multitude of reference voltage sources would be needed and, consequently, an enormous layout area would be required (Fig. 3).

As an example of a multiple-valued computation system, we designed, using the single-electron circuit in Fig. 2, a multiple-valued Hopfield neural network that solves the quadratic integer-programming problem. A computer simulation demonstrated that the network system can converge to its optimal state that represents the solution to the problem.

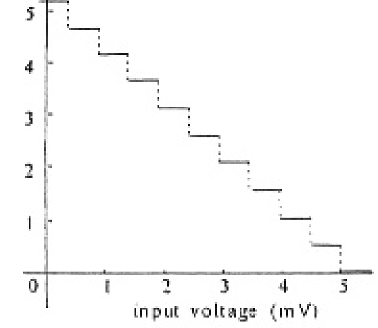

Fig. 1 Staircase transfer function. The voltages on the scale are for the single-electron circuit given in Fig. 2.

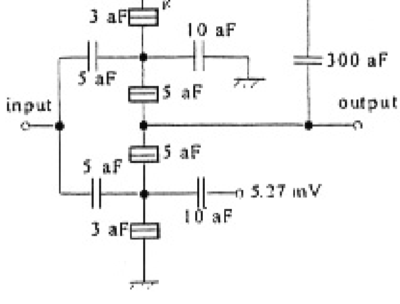

Fig. 2 Single-electron circuit for producing the staircase transfer function, together with a sample set of device parameters.

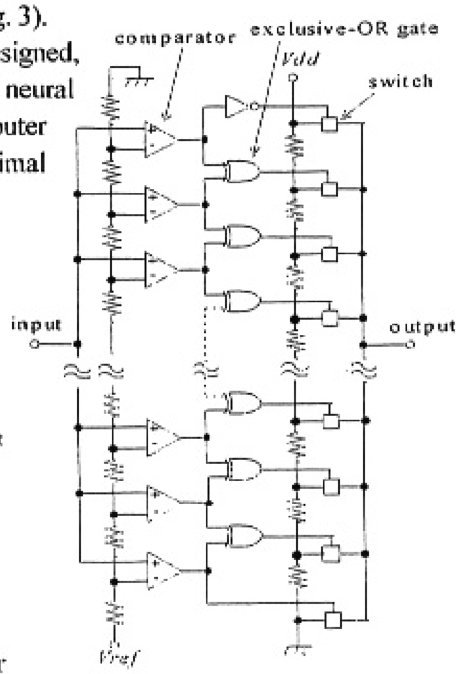

Fig. 3 CMOS circuit for producing the staircase transfer function.