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Eliciting the Potential Functions of Single-Electron Circuits

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SUMMARY This paper describes a guiding principle for designing functional single-electron tunneling (SET) circuits—that is a way to elicit the potential functions of a given SET circuit by using as a guiding tool the SET circuit stability diagram. A stability diagram is a map that depicts the stable regions of a SET circuit based on the circuit's variable coordinates. By scrutinizing the diagram, we can infer all the potential functions that can be obtained from a circuit configuration. As an example, we take up a well-known SET-inverter circuit and uncover its latent functions by studying the circuit configuration, based on its stability diagram. We can produce various functions, e.g., step-inverter, Schmidt-trigger, memory cell, literal, and stochastic-neuron functions. The last function makes good use of the inherent stochastic nature of single-electron tunneling, and can be applied to Boltzmann-machine neural network systems.

key words: *single-electron, SET, logic, circuit, stability diagram, Boltzmann machine*

1. Introduction

Essential to the opening up of future directions in electronics is the development of circuit technologies that can implement complex and high-level functions in commpact construction. The single-electron tunneling (SET) circuit is a promising candidate for promoting such next-generation technologies. This paper introduces a guiding principle for designing functional SET circuits—that is a way of eliciting the potential functions of a given SET circuit, using the SET circuit stability diagram as a guiding tool. The authors hope that it will stimulate the thinking of readers who are aiming to create novel functions by using single-electron tunneling circuit.

The SET circuit [1], [2] is an electronic circuit that consists of tunnel junctions and capacitors. For a general explanation, see Ref. [3]. A SET circuit has a number of nodes or islands that are interconnected by means of tunnel junctions. Its internal state is determined by the configuration of its electrons (i.e., the pattern in which the excess electrons are distributed among the islands). This pattern is expressed by a set of numbers that indicates the number of excess electrons on the islands. The circuit varies its electron configuration through tunneling in response to the inputs, and thereby changes its output voltage as a function of the inputs. A change of the electron configuration caused by a tunneling event, at low temperatures, can occur only when the energy of the circuit decreases along with the tunneling. This phenomenon is called the *Coulomb blockade*. Owing to this, the SET circuit shows strong nonlinearity in its characteristics. It also shows complex internal states: at given inputs, it may be monostable, bistable, multistable, or unstable. This is the conspicuous property that distinguishes SET circuits from CMOS circuits. It is therefore probable that various functions can be produced from SET circuits by use of a simple circuit configuration.

A SET circuit changes its state to decrease its free energy; hence, the circuit operates as an organic whole (this is true even if the circuit is composed of a number of subcircuits). Therefore any circuit has to be designed taking into consideration the global stability of the whole circuit. Because a SET circuit has complex internal states, a "guide map" is needed to grasp the overall situation of the circuit. The guide map or tool for this purpose is known as the *stability diagram*, the concept of which was first introduced by Likharev [1]. This is a diagram that illustrates the internal states of a SET circuit in a multidimensional space of circuit variables (namely, the voltages of powers and inputs, and the capacitances of tunnel junctions and capacitors). Looking at a stability diagram, we can see the changes of the internal states, the stability, and the output values, as functions of the circuit variables. And, most importantly, we can obtain therefrom an insight into the circuit design. Given the stability diagram of a SET circuit, we can unveil all the potential functions that can be obtained from the circuit.

The purpose of this paper is to show with examples that we can elicit various useful functions from a given SET circuit by using the stability diagram for the circuit as a guiding tool. In the following sections, we first outline the concept of a stability diagram (Sect. 2). After that, we take up the *Tucker's inverter* as a sample circuit, and show that various functions, besides the well-known inverter characteristic, can be elicited. We demonstrate the design of three instances, namely a step inverter, a Schmidt trigger circuit, and a memory-cell circuit, using the stability diagram (Sect. 3). We also present an example for utilizing the inherent stochastic nature of single-electron tunneling,

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to wit, a design of a Boltzmann-machine neuron circuit. By designing appropriate parameters in the sample circuit, we can implement the function of the stochastic neuron that produces a random 1-0 bit stream with the probability controlled by an input—a task that is difficult for a conventional circuit that uses CMOS devices (Sect. 4).

2. The SET Circuit Stability Diagram

As mentioned earlier, a SET circuit has complex internal states and changes its state in various ways as a result of tunneling. The tunneling is regulated by the Coulomb blockade depending on the bias conditions for the tunnel junctions, and the bias conditions are in turn determined by circuit variables (the applied voltages and the capacitance values). (In the following, low temperature is assumed for the occurrence of the Coulomb blockade.) To hold a state of the circuit stable, or to prevent tunneling through a junction, a bias criterion for each tunnel junction must be established. If one or more bias criterion is disturbed, the circuit changes into another state by means of tunneling. It is difficult to predict which state the circuit will take with variables of given values, and therefore a guide map for the circuit condition is needed.

Such a guide map is called a stability diagram. It depicts the internal states of a SET circuit in a multidimensional space of circuit variables. Its concept is as follows. The bias criteria necessary to maintain a circuit in a stable state are given as a combination of inequalities, each of which represents a condition for maintaining the circuit energy minimum. The inequalities involve all the circuit parameters as variables, so the stable bias region for a given state is illustrated as a hyper solid surrounded by a number of hyper surfaces in a circuit-variable space. (For instance, the sample circuit in Fig. 2 has 11 variables—two voltage variables, V_{in} and V_{dd}, and nine capacitance variables. Accordingly, the stable bias region is drawn in an 11-dimensional space.) Each hyper surface corresponds to a threshold for tunneling through a junction in one direction; therefore, if the number of the tunnel junctions is N, then $2N$ hyper surfaces exist. (We assume that a tunnel junction is bilateral. A directional tunnel junction [4], [5] can be also assumed, but we will not discuss it here.) For a different state of the circuit, a different set of hyper surfaces exists that determine the hyper solid of a stable region. The stability diagram is a map that illustrates all the hyper solids that represent all possible states of the circuit.

To illustrate a stability diagram on a sheet of paper, we have to reduce the diagram to a two-dimensional representation. For this purpose, we select two of the variables and assume the others to be constant. In general it is convenient, in designing a circuit, to choose the input voltages for the circuit as the variables. If the circuit has one and only one input, it is advisable to use as the other variable the voltage of another voltage source in the circuit. In such a two-dimensional stability diagram with two voltage variables, the hyper surfaces and the hyper solids are reduced to straight lines and polygons. (For examples of stability diagrams with two voltage variables, see Refs. [1], [2], [6], and [7])

An example of such a two-dimensional diagram is given in Fig. 1(a). (The SET circuit under investigation is assumed to have N islands and two or more voltage sources, considering an input to be a voltage source. We take the voltages of two sources as variables, and assume the other voltages, if any, to be constant.) In the figure, the V_1- and V_2- axes indicate the values of the two voltage variables. The unshaded region denoted by $(a_1, a_2, \cdots, a_K, \cdots, a_N)$ indicates a stable (monostable) region, where $a_1, a_2, \cdots, a_K, \cdots, a_N$ are the numbers of excess electrons stored on islands 1, $2, \cdots, K, \cdots, N$ $(1 \leq K \leq N)$. The shaded region marked *unstable region* has no stable state; tunneling occurs repeatedly here, and consequently the circuit state varies between two or more different states. In the area marked *bistable region,* two stable regions overlap,

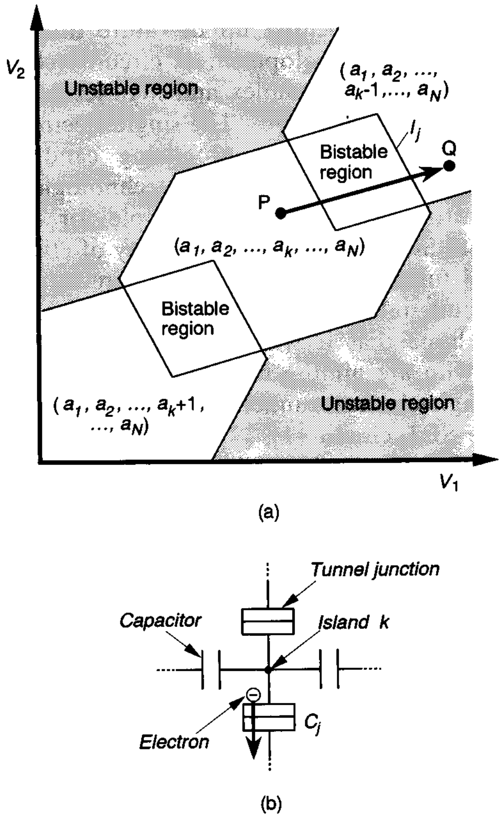

Fig. 1 Concept of the stability diagram. (a) An example of a two-dimensional stability diagram, illustrated on a plane of two voltage variables V_1 and V_2. (b) An electron tunneling, corresponding to the state change from P to Q.

and therefore the circuit can take on either state.

Suppose we cause the bias point to move from P to Q by changing the variable voltages; then the circuit state changes from $(a_1, a_2, \cdots, a_K, \cdots, a_N)$ to $(a_1, a_2, \cdots, a_K-1, \cdots, a_N)$. In this transition, a tunneling occurs at a certain tunnel junction C_j, as illustrated in Fig. 1(b), to reduce the electron number a_K on the K-th island by 1. The threshold line l_j in Fig. 1(a) corresponds to the boundary of the bias condition that produces tunneling at junction C_j.

The stability diagram can be calculated analytically for a simple SET circuit composed of a few junctions. But a circuit of greater complexity is difficult to calculate on paper, so computer simulation is needed. We have developed *a diagram simulator* in order to calculate the stability diagram for a given circuit. (The operation of a SET circuit can be simulated in the way given in Ref. [8].)

3. Function Design Using a Stability Diagram

By using the stability diagram as a guiding tool, we will be able to elicit various functions from a given SET circuit; we can produce two or more functions from a given circuit configuration, and can obtain unexpected or windfall functions from a known circuit configuration. In the following, we will take up a known SET inverter as a sample of circuit configuration and will show how many functions can be recovered from the circuit configuration. We can produce various functions, e.g., step-inverter, Schmidt-trigger, memory-cell, literal, and stochastic-neuron functions. This section will describe the first four functions. The stochastic-neuron function will be discussed in Sect. 4.

3.1 Circuit Configuration and the Corresponding Stability Diagram

As a sample circuit, we take up the inverter circuit proposed by Tucker [9] because it is the best-known example of SET-circuit elements (Fig. 2). It consists of four tunnel junctions (the junction capacitances are C_{j1} and C_{j2}), two input capacitors (C_1), two bias capacitors (C_2), and an output capacitor (C_{out}), with a voltage source V_{dd}. The input and output voltages are denoted respectively by V_{in} and V_{out}. The circuit has three island nodes (L, M, and N), and its internal state is expressed by a set of the numbers (l, m, n) of excess electrons stored on the three nodes. Tucker has determined the capacitance perameters for obtaining the inverter gain. A sample set of the parameters is:

$$C_{j1}=1\text{ aF},\ C_{j2}=2\text{ aF},\ C_1=8\text{ aF},\ C_2=7\text{ aF},$$
$$C_{out}=24\text{ aF}. \quad (1)$$

In this section, we will use this set as the capacitance

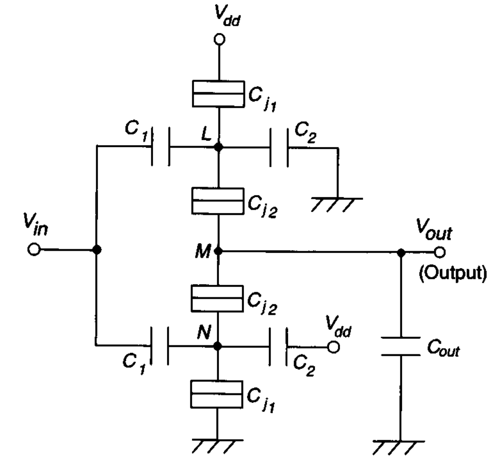

Fig. 2 Configuration of a quasi-CMOS SET inverter circuit (the Tucker's inverter) [9].

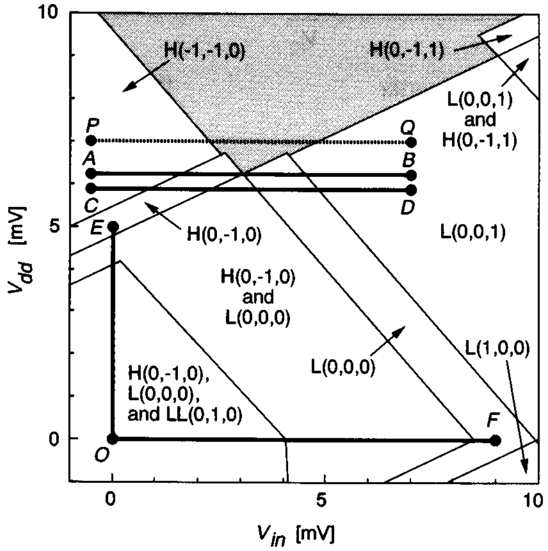

Fig. 3 Stability diagram for the circuit configuration of Fig. 2. For the capacitance parameters, see the text.

parameters. (We will also assume zero temperature and ignore the co-tunneling phenomenon.)

We calculated the stability diagram for this circuit configuration using the given parameter set. Illustrated in Fig. 3 is part of the result plotted on a plane of the two voltage variables, the input voltage V_{in} and the power voltage V_{dd}. The stable regions take on various configurations. Most regions overlap with one another. This complex structure will produce high functionality. In a set of electron numbers (l, m, n), m is the main factor of determining the output voltage, and l and n change the output voltage slightly. In the range of the voltage variables of Fig. 3, the numbers of $m=-1$, 0, and 1 produce output voltages of about 6, 0, and -6 mV, while l and n modify the output voltage by 0.7 mV or less in the same way. In Fig. 3, the approximate output voltage for each state is illustrated by putting a letter (H, L, or LL) before the electron-number set; e.g., H(0, −1, 0) indicates a state of high output voltage (about 6 mV), L(0, 0, 1) of low output voltage (about 0 mV), and LL(0, 1, 0) of much-lower output voltage (about −6 mV).

3.2 Step Inverter

The circuit configuration above is well known as the *quasi-CMOS inverter circuit*, and has been cited and studied by various researchers. As far as the authors know, the circuit has been operated conventionally under conditions such that the operation locus of the circuit crosses an unstable region, as illustrated in Fig. 3 by the segment *P-Q*. The inverter therefore has an unstable region on its transfer curve for intermediate values of the input (Fig. 4(a)).

This is not a problem for a binary-logic inverter. But it is fatal to various other applications such as threshold logic systems, neural networks, and majority-decision logic systems, because in these applications, the input for the circuit frequently takes an intermediate value. For such applications, an inverter circuit is required that is stable throughout its transfer curve (Fig. 4(b)). We named this kind of inverter a *step inverter*.

The step inverter can be obtained by designing the circuit so that the operation locus will move in the segment *A-B*. This is done by setting V_{dd} equal to 6.245 mV. With the increase in input voltage, the operating point moves from *A* to *B*, and the internal state of the circuit changes as H(−1, −1, 0) → H(0, −1, 0) → L(0, 0, 0) → L(0, 0, 1), without crossing an unstable region. The first two states correspond to high outputs, while the last two to low outputs, so an abrupt change (from a high output to a low output) can be expected. The simulation result for the transfer characteristic is illustrated in Fig. 5 and agrees with our expectation. A slight discontinuity in voltage is observed on both high-output and low-output curves, and corresponds to the state transitions of H(−1, −1, 0) → H(0, −1, 0) and L(0, 0, 0) → L(0, 0, 1). But this is not a critical problem in most applications. If necessary, the discontinuity can be removed by adjusting the capacitance parameters of the circuit.

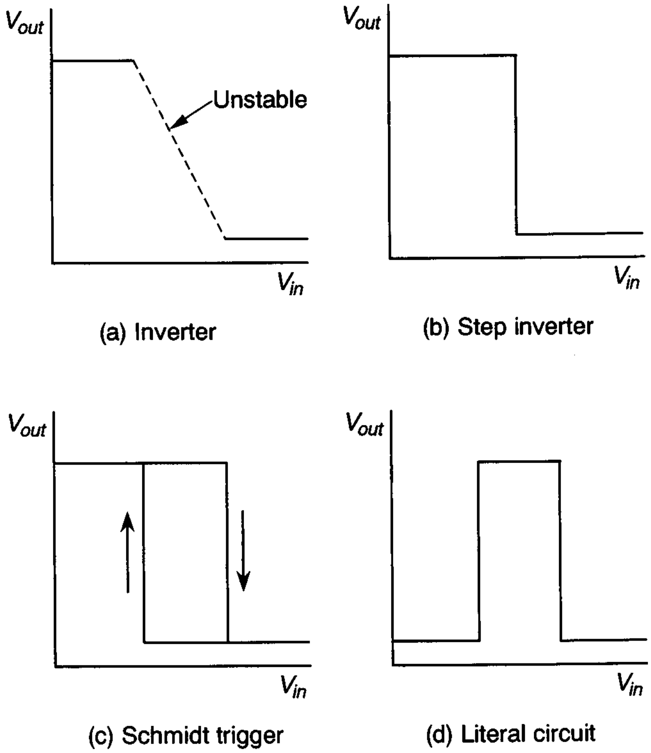

Fig. 4 Transfer characteristics (an input voltage vs. output voltage curve) for various functions. (a) Inverter with an unstable region, (b) step inverter, (c) Schmidt trigger circuit, and (d) literal circuit.

3.3 Schmidt Trigger Circuit

A Schmidt trigger circuit is a threshold circuit that has

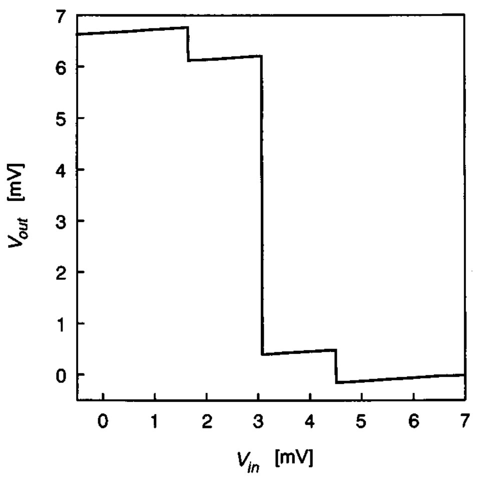

Fig. 5 A transfer curve of the step inverter circuit.

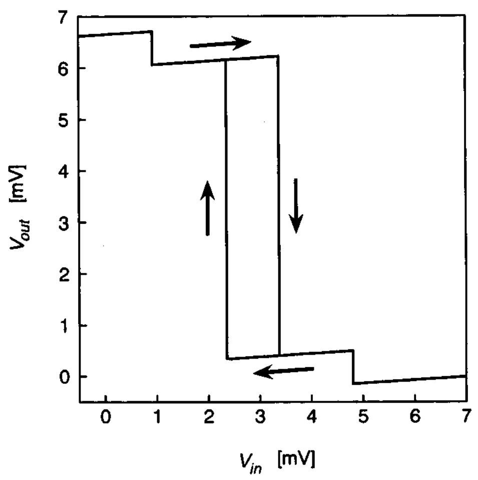

Fig. 6 A transfer curve of the Schmidt trigger circuit.

a hysteresis characteristic on its transfer curve (Fig. 4 (c)). It is mainly used to convert noisy alalog signals to binary signals without chattering.

This function can be obtained by setting the operation locus on the segment *C-D*. In the bistable region denoted by *H (0, −1, 0) and L (0, 0, 0)*, the circuit will maintain its state the same as just before entering this region. It can therefore be expected that the threshold voltage of the circuit will be higher for an increasing input and lower for a decreasing input; this condition results in a hysteresis characteristic. The simulated transfer characteristic (Fig. 6) agrees with our expectation, and the hysteresis is clearly observable. The width of the hysteresis region can be set up as desired by adjusting the power voltage V_{dd} (it can be also controlled by adjusting the capacitance parameters).

3.4 Memory Cell Circuit

A memory function can be obtained by using a Schmidt trigger circuit, but there is a better way, as described below.

Let us consider setting the operation locus on the two segments *O-E* and *O-F* in Fig. 3. Point *O* has two stable states, H(0, −1, 0) and L(0, 0, 0) (we here ignore the third stase LL(0, 1, 0), because this state is *not* induced unless the power voltage V_{dd} is set to be negative), while point *E* has the single state H(0, −1, 0) and point *F* the single state L(0, 0, 0). Therefore, moving the operating point in the manner $O \rightarrow E \rightarrow O$ changes the state to H(0, −1, 0) and one positive charge is stored on island *M*. The state H(0, −1, 0) is stable at point *O*, so the storage is non-volatile. And if the operating point is moved in the manner $O \rightarrow F \rightarrow O$, the stored positive charge is discharged and the state is reset to L(0, 0, 0). We can therefore produce a memory-cell function by using V_{dd} as a write signal and V_{in} as a reset signal. A simulation result is illustrated in Fig. 7 with the waveforms of the write and reset voltages. It can be seen that the expected memory operation has been achieved.

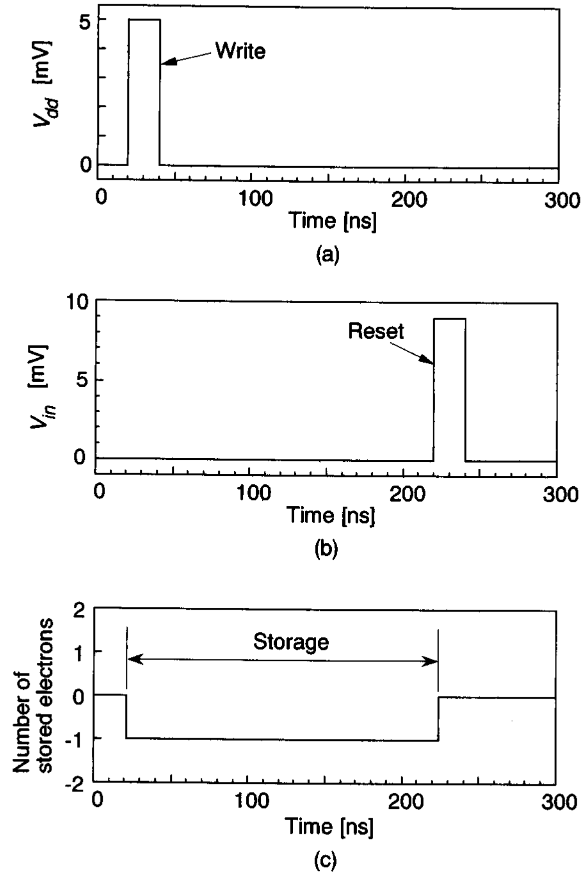

Fig. 7 An example waveform of a non-volatile memory circuit. (a) Write signal V_{dd}, (b) reset signal V_{in}, and (c) the number of stored electrons.

3.5 Literal Function Circuit

A literal function (Fig. 4(d)) (often called a window function) is a double-threshold function. It is encountered frequently in multivalued logic applications. The literal function can be produced by designing a circuit such that the circuit changes its state from a low-output state to a high-output state and returns to a low-output state with an increase of input voltage. This function can be achieved by using the same circuit configuration as above. For this purpose, however, we have to change the circuit parameters drastically to create a new stability-diagram configuration that is suitable for the literal function. We will therefore pursue this matter at the next future opportunity.

4. Neuron Circuit Utilizing the Stochastic Nature of Single-Electron Tunneling

One promising area of research on SET circuits is that of the development of functional circuits that utilize the inherent stochastic nature of single-electron tunneling. For this development, we must find applications that make good use of the unstable regions in SET circuits. An example of such an application is a *Boltzmann machine neuron circuit*. In the following, we will describe the concept of Boltzmann machine neural networks and the function required for the neuron. Then we will propose a circuit configuration for implementing the required function. The desired circuit can be achieved by modifying the Tucker's inverter circuit.

4.1 The Concept of the Boltzmann Machine Neural Network

The Boltzmann machine is a kind of feedback neural network that can solve various problems in subjects such as combinatorial optimization, classification, and

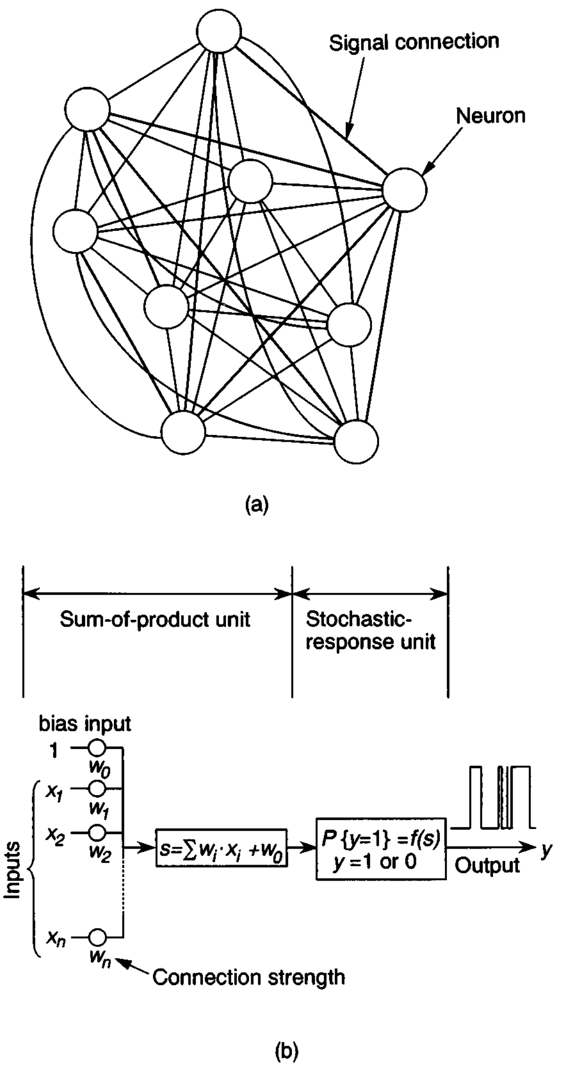

Fig. 8 Boltzmann-machine neural network and its neuron. (a) Concept of the network, (b) function of a Boltzmann-machine neuron.

association. Figure 8 (a) presents a schematic diagram of a Boltzmann machine neural network. This consists of a large network of neurons that are interconnected bidirectionally with signal connections having various connection strengths. Each neuron receives input signals from other neurons and sends output signals to other neurons. The neuron has two output states, either 1 or 0, and changes its state according to the inputs, following a stochastic transition rule; i.e., the output is a random 1-0 bit stream. All neurons operate in parallel and each adjusts its own state to those of all the others. After some processing time, all the neurons finally reach maximal consensus about their individual states, and the whole network then stabilizes in a global configuration. For details, see Refs. [10] and [11].

The structure of mathematical problems such as combinatorial optimization can be mapped onto the structure of a Boltzmann machine by deciding the connection pattern and connection strengths of the neurons. In this way, finding the optimal solution to a problem can be reduced to finding the optimal configuration of the Boltzmann machine. The unique and important feature of the Boltzmann machine is its method of operation, which uses stochastic neuron-state transition and simulated annealing algorithms. This allows the Boltzmann machine to reach a configuration that is globally optimal (and thereby an optimal solution) without falling into configurations that are only locally optimal. (This is a problem with other neural network models.) Because of this, the stochastic output of the neuron is the most important feature of Boltzmann machine.

4.2 Required Function for the Neuron Circuit

The basic concept of the Boltzmann machine neuron is illustrated in Fig. 8 (b). It has two constituents, a sum-of-product unit and a stochastic-response unit. The sum-of-product unit has a number of input connections and local memory that stores connection strengths w_i (positive or negative analog values). Also, it receives input signals x_i (1 or 0) (and bias input that controls the threshold of the neuron) from other neurons and produces the weighted sum of inputs $s(=\sum w_i \cdot x_i + w_0)$. The stochastic-response unit is peculiar to the Boltzmann-machine neuron. It generates an output, 1 or 0, updating the output state every moment, following a given probability that depends on the input value of s. The probalility function for a state 1 is usually chosen to be the sigmoid function, expressed as

$$f(s) = \frac{1}{1+\exp(-s/T)}, \text{ or } f(s) = \frac{1}{1+\exp(s/T)}, \tag{2}$$

where T (temperature) is the control parameter that slowly decreases from a large value to zero during the simulated annealing process. (Here the "temperature" need not be thermal temperature; any factor that can change the dependence of $f(s)$ on s can be used.) The shape of the function is illustrated in Fig. 9 for $f(s) = 1/(1+\exp(s/T))$, with the value of T as a parameter. Convergence of the network systems requires the capability of varying "temperature T" with continuity by means of a control signal. The probability function need not necessarily be this function; any monotonic nonlinear function can be used, provided that it becomes 1 (or 0) at large positive values of s and becomes 0 (or 1) at large negative values of s.

A Boltzmann-machine LSI for practical use must integrate thousands of neurons on a chip. The crucial problem in developing such LSIs is how to implement the generation of randomness for the stochastic opera-

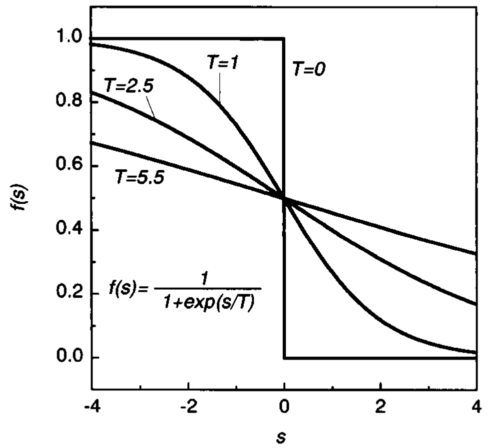

Fig. 9 Probability function $f(s)$ as a function of a weighted sum of inputs s. Illustrated is $f(s) = 1/(1+\exp(s/T))$, with T as a parameter.

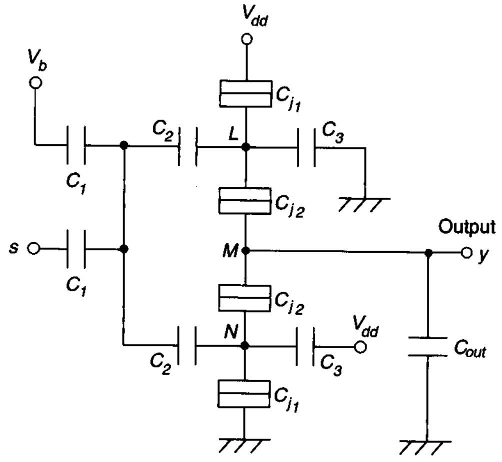

Fig. 10 Configuration of the stochastic-response unit circuit for a single-electron Boltzmann-machine neuron.

tion. Every neuron has to have its own randomness generator, because stochastic independence between the neurons is required. But presently available circuits for generating randomness, such as the thermal noise amplifier and the random bit generator, consist of many devices and consequently require a large volume of space; hence, they cannot be used for LSI implementation.

To overcome this problem, we have presented the idea that the inherent stochastic character of SET can be used for implementing the stochastic-response unit of the Boltzmann-machine neuron [12]. We will describe in the next section a single-electron neuron circuit that gives practical form to this idea. The point is to operate a SET circuit in unstable regions to produce stochastic output. As described in 2.1, a SET circuit in unstable regions varies its internal state between two more states, so an output of a random 1-0 bit stream can be expected. If the probability for an output 1 (or 0) can be changed in response to an input, then this phenomenon will be useful for the stochastic-response unit of the Boltzmann-machine neuron.

4. 3 Designing a SET Neuron Circuit

The stochastic-response unit has to be designed in a such configuration that the "temperature T" of the probability function can be changed by a control voltage. This is done by modifying the Tucker's inverter circuit. Illustrated in Fig. 10 is the circuit we propose for a stochastic response unit. The circuit receives a voltage input s from a sum-of-product unit to generate its internal state and produces the corresponding voltage output y. The bias voltage V_b adjusts the threshold of the circuit by adding an offset to the input, and the value of the "temperature T" is changed by the control voltage V_{dd}.

For this circuit configuration, we designed the stability diagram for operating the circuit under unstable conditions around zero inputs. A desirable set of the capacitance parameters is:

$$C_{j1}=1\text{ aF},\ C_{j2}=2\text{ aF},\ C_1=12\text{ aF},\ C_2=4\text{ aF},$$
$$C_3=10\text{ aF},\ C_{out}=24\text{ aF}. \quad (3)$$

Assuming this capacitance set, we drew the stability diagram in a three-dimensional space of three voltage variables (s, V_b, and V_{dd}). In Figs. 11(a) through 11(d), a part of the diagram is illustrated on a plane of the two voltage variables, the input voltage s and the bias voltage V_b. The control voltage V_{dd} is: (a) 5.938 mV, (b) 6.2 mV, (c) 6.3 mV, and (d) 6.5 mV. Figures 11(a) through 11(d) correspond to an increase of the "temperature T"; $T=0$ in Fig. 11(a) and T is at maximum in 11(d).

Four stable regions, i.e. states H(−1, −1, 0), H(0, −1, 0), L(0, 0, 0), and L(0, 0, 1), can be seen on the diagram; the first two states produce a high output voltage (an output 1), while the last two produce a low output voltage (an output 0).

We operated the circuit so that the operating point would move on the segment PQ illustrated in Figs. 11(a) through 11(d). It can be expected that the probability for generation of an output 1 can be changed from 1 to 0 continuously by moving the operating point from P to Q. A simulation result is illustrated in Fig. 12 for the condition of Fig. 11(c) (i.e., $V_{dd}=6.3$ mV). Figure 12 shows the output voltage waveform (a rondom 1-0 bit stream) for three instance values of the input voltage: (a) $s=-2$ mV (point X in Fig. 11(c)); (b) $s=0$ mV (point Y in Fig. 11(c)); (c) $s=2$ mV (point Z in Fig. 11(c)). It can be seen that the probability for an output 1 can be changed by the input s, where the state of high output is dominant for a low value of s, while the state of low output is dominant for a high value of s. Intermediate states can also be generated, but this is not a problem because

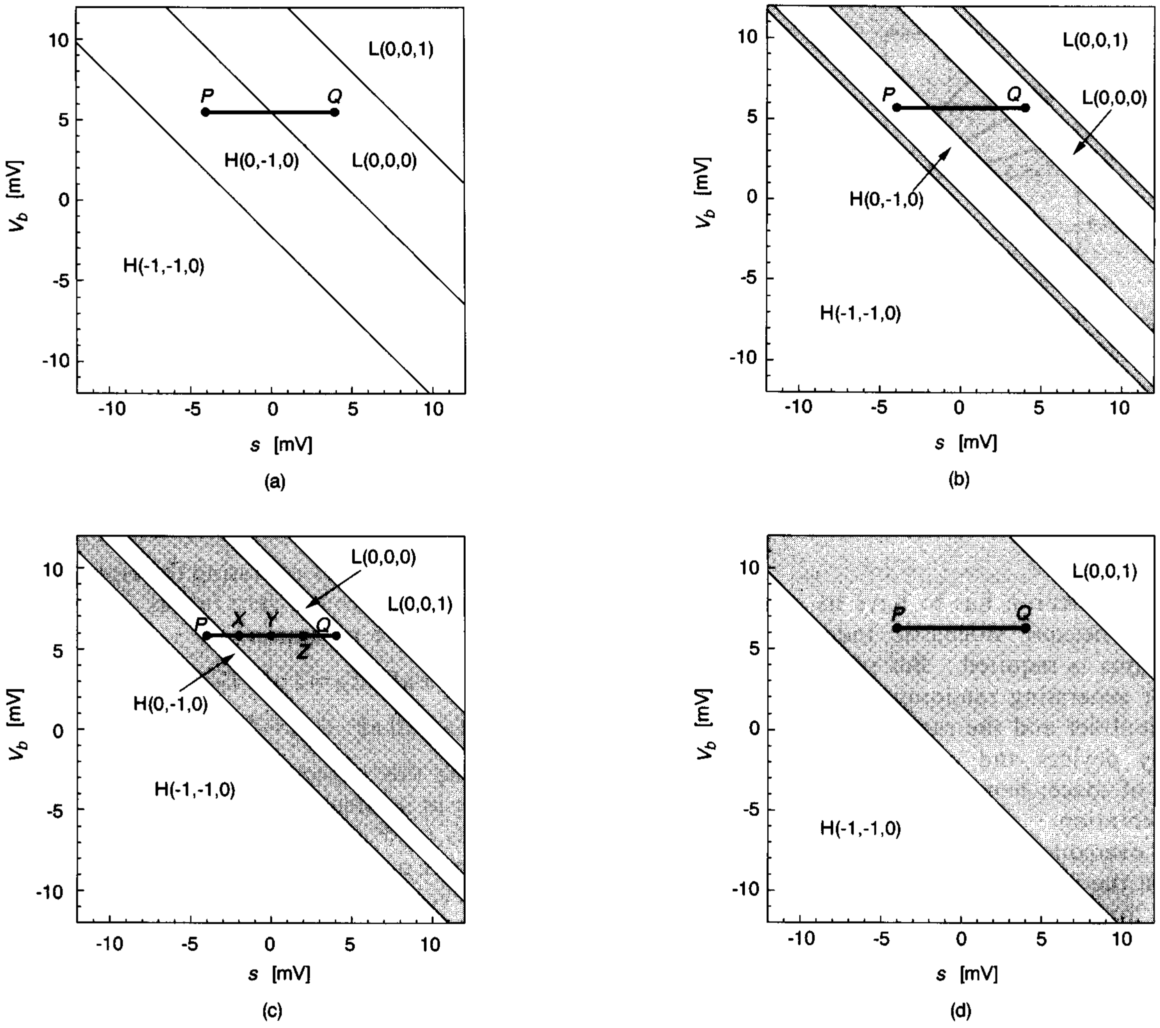

Fig. 11 A stability diagram for the circuit configuration of Fig. 10, plotted on a plane of the input voltage s and the bias voltage V_b. Capacitance parameters are: $C_{j1}=1$ aF, $C_{j2}=2$ aF, $C_1=12$ aF, $C_2=4$ aF, $C_3=10$ aF, $C_{out}=24$ aF. Figures 11 (a) through 11 (d) correspond to an increase of the control voltage V_{dd}, therefore correspond to an increase of the "temperature T." The value of V_{dd} is: (a) 5.938 mV, (b) 6.2 mV, (c) 6.3 mV, and (d) 6.5 mV.

their duration is always short regardless of the input voltage value. In this example, the circuit changes its internal state in a cycle of $L(0,0,0) \rightarrow L(-1,0,0) \rightarrow H(0,-1,0) \rightarrow H(0,-1,1) \rightarrow L(0,0,0)$. Similar operation can be observed in other V_{dd} values. In the condition of Fig. 11 (a), which corresponds to "temperature T"=0, the circuit acts as a step inverter without unstable operation.

The probability for an output 1 is illustrated in Fig. 13 as a funcction of the input voltage, with V_{dd} (and V_b) as a parameter. It is obtained by observing the output 1-0 stream for 1 μs and measuring the total duration of an output 1. It can be seen that a probability function required for the Boltzmann-machine neuron can be obtained very easily. It should be noted that the "temperature T" of the sigmoid characteristic can be controlled by changing the value of V_{dd}. This controllability of the "temperature T" is indispensable to the network system operation.

5. Conclusion

We introduced a guiding principle for designing functional SET circuits—namely, a way of bringing out the functionality of SET circuits, using the stability diagram of SET circuits as a guiding tool. A stability diagram is a map that illustrates the stable regions of a SET circuit on the circuit-variable coordinates, and it gives us an insight into the operation of the circuit. From the stability diagram, we can unveil all the

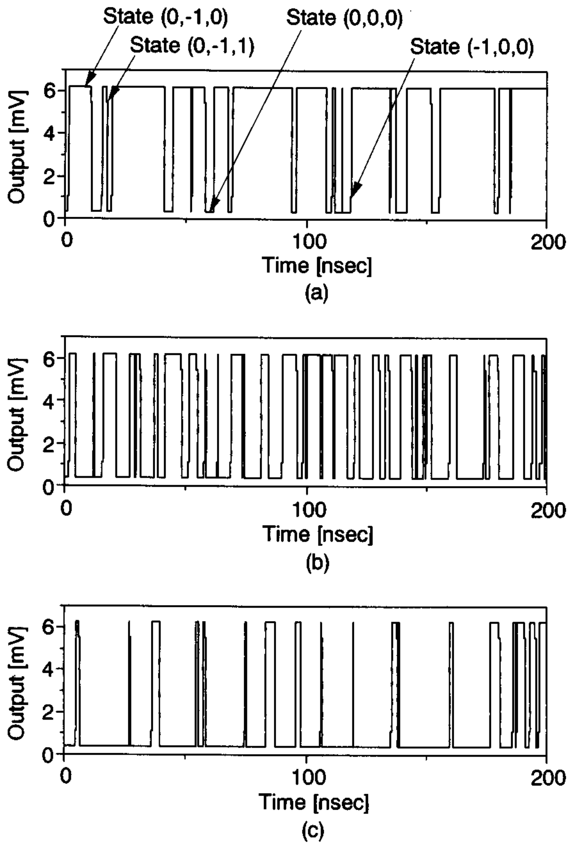

Fig. 12 Output voltage waveform for the stochastic-response unit circuit with $V_{dd}=6.3$ mV and $V_b=5.9$ mV. Simulated for three input voltages: (a) $s=-2$ mV (point X in Fig. 11(c)), (b) $s=0$ mV (point Y in Fig. 11(c)), and (c) $s=2$ mV (point Z in Fig. 11(c)). Tunnel resistance is set at 5 MΩ for four junctions. Temperature is 0 K.

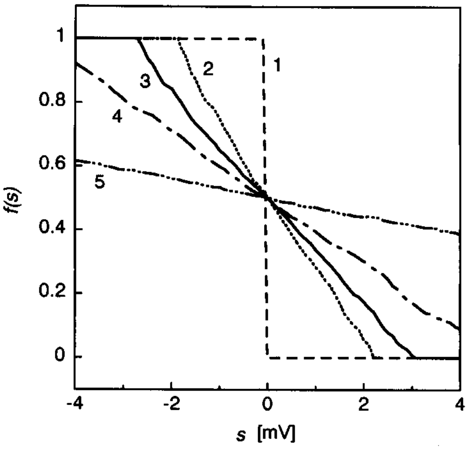

Fig. 13 Probability function for the circuit with the parameters of Figs. 11 and 12. The probability for generating an output 1 is illustrated as a function of the input voltage s, for differet values of "temperature T." The "temperature T" is controlled by V_{dd}. Curve 1 is for $V_{dd}=5.938$ mV ($V_b=5.515$ mV), curve 2 for $V_{dd}=6.2$ mV ($V_b=5.7$ mV), curve 3 for $V_{dd}=6.3$ mV ($V_b=5.9$ mV), curve 4 for $V_{dd}=6.5$ mV ($V_b=6.3$ mV), curve 5 for $V_{dd}=7.5$ mV ($V_b=9.5$ mV).

potential functions that can be obtained from the circuit configuration. As an example, we took up the Tucker's inverter circuit, and elicited the latent functions of the circuit configuration, by investigating its stability diagram. We were able to produce various functions, e.g., a step-inverter, a Schmidt trigger, a memory cell, a literal, and a stochastic-neuron function. The last function makes good use of the inherent stochastic character of single-electron tunneling, and has application to Boltzmann-machine neural network systems. We will be able to produce or obtain unexpected or windfall functions from a given circuit configuration by investigating the stability diagram of the circuit configuration.

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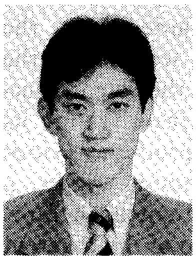

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