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Novel Functional Nonlinear Nanodevices

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Abstract—Novel functional nonlinear nanodevices based on "nature-inspired" and "bio-mimetic" techniques are discussed. Here, the targeted nanodevices are single-electron devices in particular. The important factor in producing nature-inspired and bio-mimetic circuits or devices is the consideration of how natural world phenomena and biological behavior relate to targeted nanodevices. To construct nature-inspired or bio-mimetic circuits, "perfect mimicking" and "rough mimicking" techniques can be used. It is essential for each type of system to have nonlinear oscillators because original systems based on natural phenomena or biological behavior can be represented as nonlinear oscillator systems. Nature-inspired and bio-mimetic single-electron circuits are described as demonstrations. These demonstrations indicate that such circuits based on the proposed approaches are representative of nature-inspired and bio-mimetic circuits and that they will be considered useful and functional devices.

1. Introduction

Nano-scaled devices, e.g., single-electron devices, single molecule devices, and quantum dot devices, are of particular interest because they have unique properties such as nonlinearity and high integration, and unit elements of them can be designed, constructed, and fabricated. Therefore, many researchers have tried to design and develop useful and functional systems for the construction of novel information-processing devices. For instance, CMOS-like nanodevices were proposed at the dawn of nanodevice studies. Another approach, the "nature-inspired" or "bio-mimetic" technique, is based on natural world phenomena and biological behaviors for the purpose of developing novel functional nanodevices. The natural world and living things often provide us with useful hints on how to produce new materials and devices. For instance, from the perspective of electrical engineering, various kinds of natural world phenomena or the behaviors of living things can be assumed to process information very efficiently. Therefore, mimicking such behaviors is important for producing novel and functional information processing devices. An important factor in producing nature-inspired (or bio-mimetic) devices is matching the behaviors of the targeted devices with those of natural world phenomena or living things. The successful mimicking of such behaviors is expected to result in the production of unique devices.

In this study, unique behaviors and properties in the natural world (including those of living things) have been focused upon to design novel, unique, and functional nanoelectronic circuits, i.e., single-electron circuits, which are our targeted devices. A single-electron circuit can control an individual electron by controlling a quantum effect, i.e., the Coulomb blockade effect [1]. The single-electron circuit has tunneling junctions as main components. Since it can control only a few electrons in operation, the single-electron circuit should show nonlinear operation and extremely low power consumption. However, use of the single-electron circuit has been somewhat problematic. For example, the most appropriate information-processing architecture has yet to be decided. In addition, the circuit is very sensitive to noise generated by heat or light. Noise can cause circuit malfunction. For those problems, the approaches of this study present strong candidates for solutions. Here, the previous studies of the following actual proposed nature-inspired or bio-mimetic single-electron circuits and their applications are discussed. Moreover, it is considered how useful they are on the basis of nonlinearity.

- Mimicking the behavior of chemical reaction-diffusion systems
  - Single-electron "reaction-diffusion" circuit and its applications [2, 3]
- Mimicking the behavior of living things in the natural world
  - Single-electron "slime-mold" circuit and its applications [4, 5]
  - Single-electron "soldier crab" ball gate circuit and its applications [6]
  - Single-electron "ant group" circuit and its applications [7]
- Mimicking the function of brains, i.e., neural networks
  - Single-electron "stochastic resonance" circuit and its applications [8, 9, 10]
  - Single-electron "associative memory" circuit and its applications [11]

2. Mimicking Behavior of Reaction-Diffusion Systems

Originally, the reaction-diffusion (RD) system is a chemically complex system in a nonequilibrium, open state where chemical reactions and material diffusion coexist. In such a system, many elementary reactions proceed with the participation of various chemical substances, influencing one another through the synthesis and resolution of the substances. As a result, an RD system exhibits high-order nonlinear behavior and produces various dynamic phenomena unpredictable from an equilibrium state. A particular feature of the RD system is its generation of a dissipative structure. As system parameters change, varied dissipative structures appear as spatiotemporal patterns of chemical concentration. The typical pattern is traveling excitable waves, and the waves can be used for a certain type of "wave computing system." The behavior of RD systems can be expressed by the "RD equation," a partial differential equation with chemical concentrations as variables:

$$\frac{\partial \boldsymbol{u}}{\partial t} = f(\boldsymbol{u}) + D\Delta\boldsymbol{u} \qquad (\boldsymbol{u} = (u_1, u_2, u_3, \cdots)), \qquad (1)$$

where t is time, $\boldsymbol{u}$ is the vector of chemical concentrations, u_i is the concentration of the ith substance, and D is the diagonal matrix of diffusion coefficients. Nonlinear function $f(\boldsymbol{u})$ is the reaction term that represents the reaction kinetics of the system. Spatial derivative $D\Delta\boldsymbol{u}$ is the diffusion term that represents the change of $\boldsymbol{u}$ due to the diffusion of the substance. The RD system can be considered an aggregate of coupled chemical oscillators as described in Fig. 1. Each oscillator represents the local reaction of chemical substances and generates nonlinear dynamics $d\boldsymbol{u}/dt = f(\boldsymbol{u})$ that correspond to reaction kinetics in Eq. (1). The oscillator interacts with its neighbors through nonlocal diffusion of substances; this corresponds to the diffusion term in Eq. (1) and produces dynamics $d\boldsymbol{u}/dt = D\Delta\boldsymbol{u}$.

To construct electrical RD systems mimicking the behavior of the RD systems, manufacturers can choose one of two useful methods. The first method that represents mathematical models (Eq. (1), for example) as circuits or devices can be considered a "perfect mimicking type." Conversely, the other one that represents structures (Fig. 1, for example) as circuits or devices can be considered a "rough mimicking type." That is, if the manufacturers choose the second method, they prepare certain arrayed nonlinear oscillators that interact with their neighbors. An important point in the construction of electrical RD systems is the consideration of the correspondence of the natural phenomena to the devices or the circuits. The author considers that strict mimicking based on mathematical models as described above, i.e., the perfect mimicking type, is not always necessary. Here, a single-electron RD circuit designed on the basis of the rough mimicking technique is described in Fig. 2 (a). The main component of the circuit is an SE oscillator that consists of a tunneling junction, C_j, and a high resistance, R, connected in a series at a node and biased by a positive voltage, V_d, or a negative one, $-V_\mathrm{d}$. It has a threshold value for electrons to tunnel. When the electron tunneling occurs in a V_d-biased SE oscillator, for example, the voltage V_node of the node of the oscillator suddenly changes from positive to negative. This sudden change of voltage triggers other electron tunnelings in adjacent oscillators. As a result, the circuit can generate traveling voltage waves (distinctive spatiotemporal patterns) in the same way as the original RD system, caused by the occurrence of an electron tunneling in each SE oscillator in the circuit, as shown in Fig. 2 (b). Such results provide evidence that the rough mimicking technique is certainly useful for constructing certain types of nature-inspired circuits.

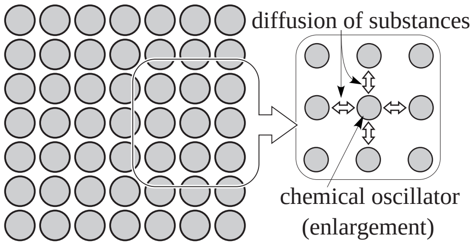

Figure 1: Simplified model of RD systems, consisting of many chemical oscillators [2].

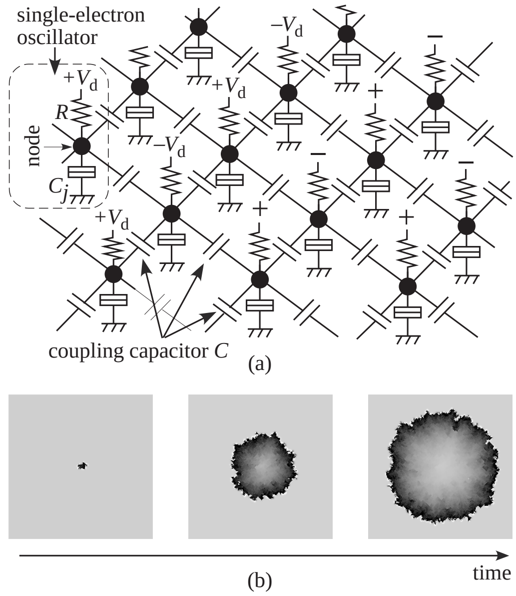

Figure 2: (a) Circuit configuration of single-electron RD circuit [2] and (b) snapshots of traveling voltage wave that is generated by the circuit (simulated) [2] .

3. Mimicking Behavior of Living Things

Here, novel information processing circuits mimicking the behavior of living things are discussed. In the natu-

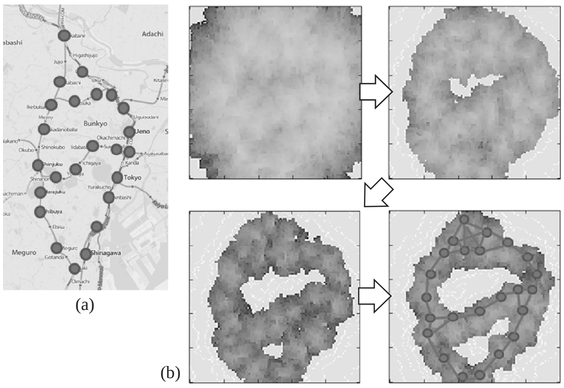

Figure 3: (a) 24 JR railway network stations in Tokyo, Japan, chosen to demonstrate circuit operation (marked on a Google map). (b) Snapshots of generated patterns that can be obtained when dilation and contraction circuits operate [5]. Circuits can show actual JR-network-like patterns.

ral world, evolution favors the efficient behavior of living things. That is, the biological systems of living things behave in various ways to keep energy to a minimum (they try to remain in a stable state). Such behavior can be considered as “efficient operation” and “functional operation” from the perspective of electrical engineering. Moreover, systems that behave in a highly efficient manner can be considered to be highly perfect. Therefore, such systems should be considered as references for the creation of new circuits and devices. To create highly efficient and highlyfunctional circuits and devices, manufacturers can apply the perfect mimicking or the rough mimicking techniques described above. The author has studied some organism- and creature-inspired single-electron circuits [4, 5, 6, 7]. For example, when constructing a single-electron slime mold circuit, two phenomena must be represented for the circuit in terms of preserving the topology of the original slime mold. One is “dilatation” behavior, and the other is “contraction” behavior. Moreover, behaviors such as “scanning for food” using dilatation, “securing food,” and “effectively obtaining food” by contraction of the body can be considered. It is known that a certain type of unicellular slime mold has the capability to solve some nonlinear problems, e.g., solving maze problems and making a ringed network similar to a real railway network, despite being a unicellular animal [12, 13]. The key points for information processing are the two phenomena mentioned above. The dilation behavior can be represented as traveling waves because such waves behave similarly. Therefore, a single-electron RD circuit can be used for the dilation circuit. For the contraction circuit, for example, the medium of a special chemical called cAMP that is generated by the slime mold should be represented as the circuit. The designed circuit has been simulated and shown to operate correctly as shown in Fig. 3.

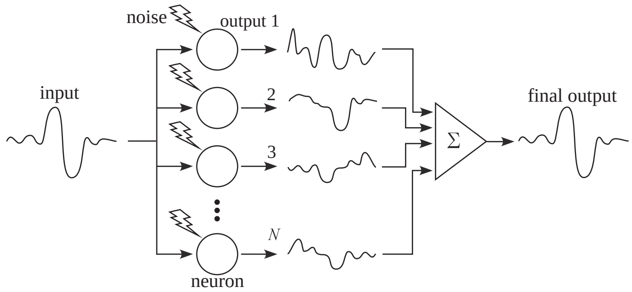

Figure 4: Schematic model of stochastic resonance proposed by Collins, et al. [14].

4. Mimicking Behavior of Brains

In this section, novel information processing circuits mimicking the functions of brains are discussed. It is known that brains have many functions for information processing. Moreover, recent reports have clarified that brains can not only overcome noise and fluctuation but can also harness them to operate correctly. In contrast, almost all conventional electrical circuits and devices must avoid them to operate. If the manufacturers succeed in developing brain-like functions for circuits and devices, they will be able to harness noise and fluctuation to operate correctly, for example. The author has studied some brain-inspired single-electron circuits [8, 9, 10, 11]. Here, a construction of a single-electron circuit that mimics a certain function of the brain is described as an example. It is generally known that circuits are very sensitive to noise and fluctuation, so many researchers have studied how to prevent such noise affecting their operation. In contrast, the brains of creatures, consisting of neurons that are very sensitive to noise, can operate correctly as a whole in a noisy environment because the brain harnesses the noise energy to process information correctly. A unique technique that imitates stochastic resonance (SR) behavior in neural networks has been focused upon to solve the noise problem. The SR phenomenon, which was discovered in studies on the brains of living things, can be considered as a type of noise-energy-harnessing system. If a circuit can take advantage of such a phenomenon as a certain function, the circuit would not only operate correctly in a noisy environment but would also show better performance than if it were not exposed to noisy conditions. It is known that a certain type of neuron can be represented as a nonlinear oscillator. Manufacturers can also construct neuromorphic single-electron circuits and single-electron neural networks because circuits can be constructed as nonlinear oscillators. Actually, neuromorphic single-electron circuits that have the stochastic resonance function based on a certain neural network model by Collins [14] (Fig. 4) have been proposed and confirmed to operate correctly, i.e., the circuits have shown better performance in noisy environments than in the absence of noisy conditions as shown in Fig. 5.

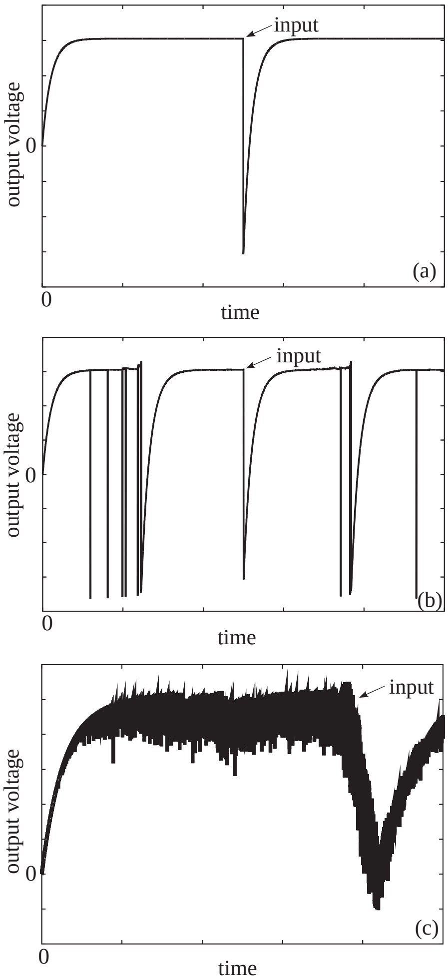

Figure 5: Sample operation of single-electron oscillator. (a) Under ideal condition ($T = 0$ [K]), (b) under thermal noise condition (1 [K]). Random outputs (errors) occur. (c) Sample operation of oscillator system based on Collins model under thermal noise condition (4.3 [K]). System can operate correctly, although a little fluctuation occurs. [15].

5. Conclusion

Nature-inspired and bio-mimetic single-electron circuits based on natural world phenomena and biological behavior were discussed. The important factor in producing nature-inspired and bio-mimetic circuits or devices is the consideration of how natural world phenomena and biological behavior relate to targeted nanodevices. To construct nature-inspired and bio-mimetic circuits, two types of techniques can be used, i.e., the "perfect mimicking type" and the "rough mimicking type." Each type of system should have nonlinear oscillators because original systems based on natural phenomena or biological behavior can be represented as nonlinear oscillator systems. As mentioned above, almost all of the original systems can operate correctly despite being placed in a noisy environment. Moreover, natural or biological systems are considered to exploit noise in their natural or biological activities. Therefore, nature-inspired and bio-mimetic circuits are expected to be able to operate correctly or exploit noise in noisy environments. Therefore, the author believes that such circuits based on the proposed approaches are representative of nature-inspired and bio-mimetic circuits and that they will be considered useful and functional devices.

Acknowledgments

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