Reaction-diffusion systems using single-electron oscillators

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Abstract

We propose a single-electron device that imitates the behavior of reaction-diffusion systems. The reaction-diffusion system (RD system) is a chemical complex system and produces various dynamic phenomena in the natural world. Constructing an electrical analog of the RD system will enable us to take a step toward creating unique, intelligent information-processing devices.

Reaction-diffusion system

The R-D system is a nonequilibrium chemical system consisting of two or more chemicals in which chemical reaction and diffusion coexist under open conditions. It produces orderly spatiotemporal patterns of chemical concentration called the *dissipative structure*; a simple instance is shown in Fig. 1 (a). Various RD systems exist in nature, and a wide variety of dynamic, self-organizing natural phenomena can be explained using the concept of the dissipative structure. Developmental biologists have the opinion that life itself is a dissipative structure produced by the natural world that is in fact a large RD system.

The RD system can be considered an aggregate of coupled chemical oscillators, as shown in Fig. 1 (b). Each oscillator represents a local reaction of chemicals and exhibits nonlinear dynamics. It interacts and correlates with its neighbors through the diffusion of chemicals and, as a result, the RD system produces orderly spatiotemporal structures.

Constructing a single-electron R-D system

To construct an electrical RD system, we propose using single-electron oscillators instead of chemical ones. The single-electron oscillator, shown in Fig. 2 (a), consists of a minute dot (nanodot), a tunneling junction (C_j), and a current source (I_s). The oscillator produces nonlinear oscillation at low temperatures because of the Coulomb blockade effect. It can be oscillatory (astable) or excitatory (monostable) if we use a current source whose current depends on the voltage of the nanodot as shown in Fig. 2 (b). The oscillator is oscillatory and exhibits self-induced oscillation, as shown in Fig. 3 (a), when the zero-current voltage (V_c in Fig. 2 (b)) is larger than the tunneling threshold of the circuit. In contrast, it is excitatory if the zero-current voltage is smaller than the threshold. In the excitatory condition, the oscillator exhibits monostable operation that is excited by an external trigger, as shown in Fig. 3 (b). We use the excitatory oscillators to construct electrical RD systems.

Dissipative structure in the RD system---simulation results

By combining the oscillators with coupling capacitors (C_L), we can construct single-electron RD systems. The point is to combine oscillators in such a way that the polarity of the current source is reversed between adjacent oscillators. Figure 4 (a) shows a one-dimensional RD system, and Fig. 5 shows a two-dimensional system. In these systems, the electron tunneling in an oscillator changes the potential of the oscillator’s nanodot. This induces tunneling in adjacent oscillators, so tunneling is transmitted throughout the system. An example of the simulated results in the one-dimensional system is shown in Fig. 4 (b). As the figure shows, tunneling transmission was delayed because of tunneling waiting time. This produced an effect analogous to diffusion, which is indispensable for constructing RD systems.

We confirmed by computer calculation that the two-dimensional RD system produced various dissipative structures, as chemical RD systems do. Figure 6 shows an instance: the system is producing a rotating spiral pattern of dot potential, which is the same behavior as that observed in the Belousov-Zhabotinsky chemical RD system and in a colony of the cellular slime molds. Different system parameters and initial conditions produce different dissipative structures. We are now developing our single-electron RD systems into bio-inspired, intelligent information-processing devices.

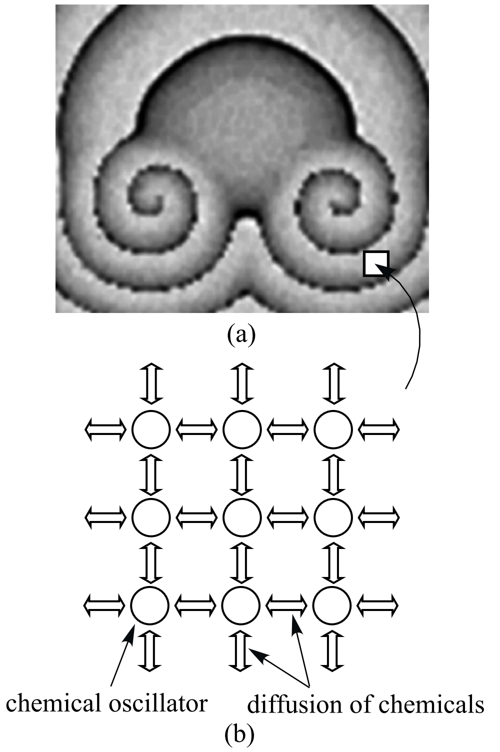

Fig. 1 Reaction-diffusion system (RD system):
(a) a dissipative structure produced by the Brusselator RD system, and (b) the schematic structure of RD systems.

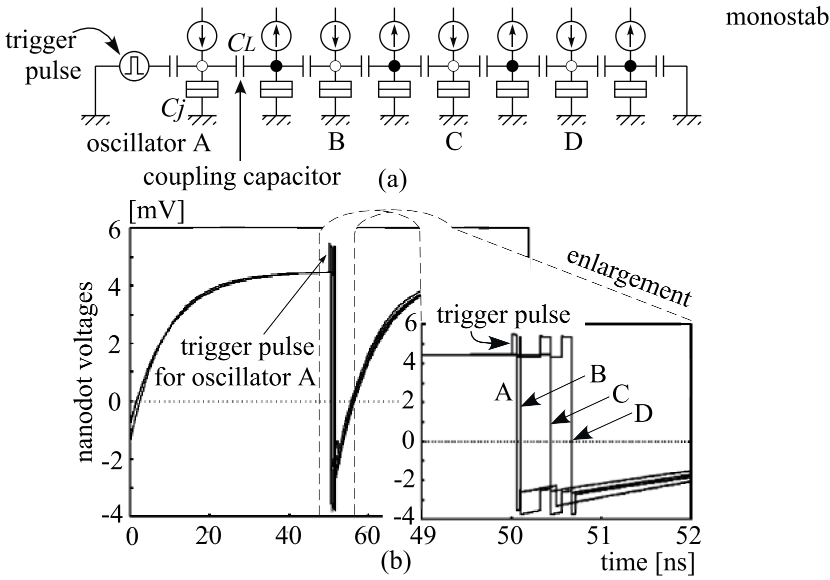

Fig. 4 One-dimensional single-electron RD system: (a) circuit configuration---a chain of the single-electron oscillators with current sources put in reverse polarity alternately, and (b) waveforms of the nanodot voltage of every other oscillator (simulated). A trigger pulse is applied to the leftmost oscillator to produce electron tunneling, and the tunneling (therefore, the jump of the nanodot voltage) is transmitted along the RD system with a delay. (Parameters: Io = 10 pA, Vc = ±4.5 mV, Cj = 10 aF, C_L = 2 aF and tunneling-junction conductance = 1 μS.)

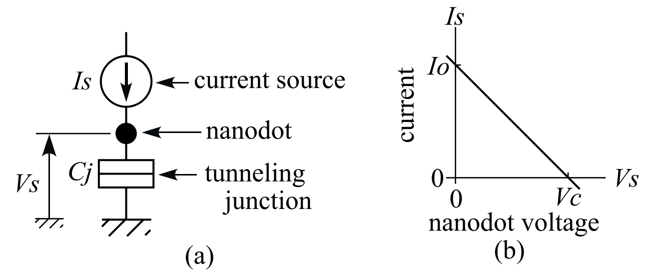

Fig. 2 Single-electron oscillator: (a) the circuit configuration, and (b) the characteristic of the current source.

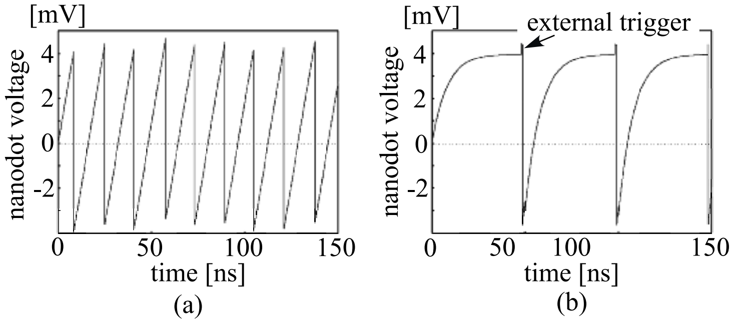

Fig. 3 Operation of the single-electron oscillator: (a) self-induced oscillation, and (b) monostable operation of a excitatory oscillator. (Parameters: Cj = 10 aF, tunneling-junction conductance = 1 μS, Io = 10 pA, Vc = ∞ for astable operation, and Vc = 4 mV for monostable operation.)

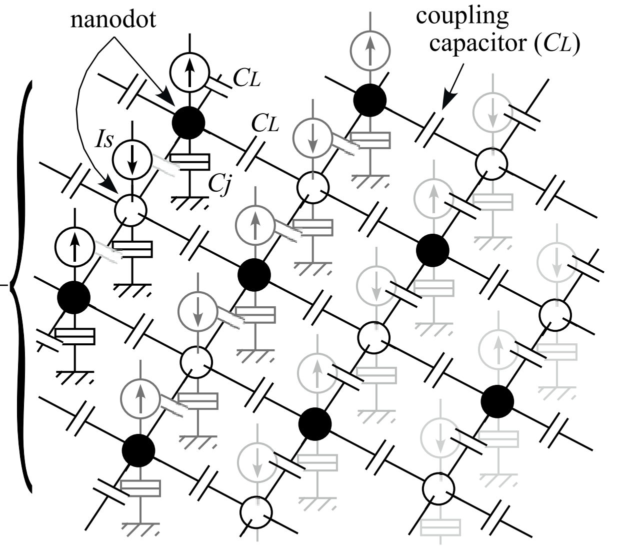

Fig. 5 Two-dimensional single-electron RD system. The white circle represents a nanodot with forward current source, and the black circle represents a nanodot with a reverse current source.

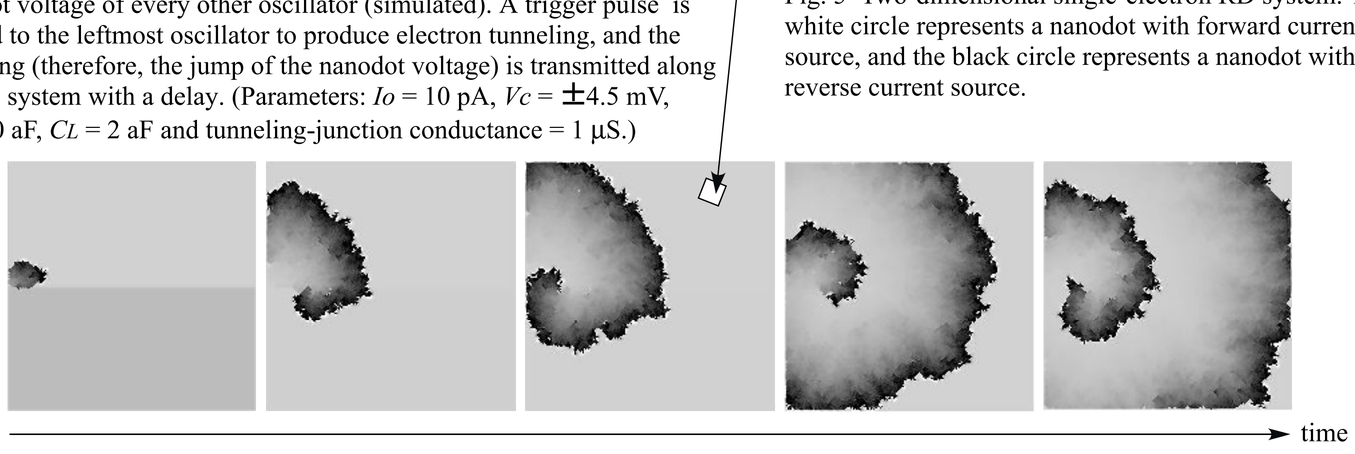

Fig. 6 A dissipative structure---a rotating spiral pattern of the nanodot voltages---produced in the two-dimensional RD system. The voltage pattern is represented with a grayscale: a bright color means a high voltage, and a dark color means a low voltage. (Parameters: Io = 120 pA, Vc = ±16.5 mV, Cj = C_L = 1 aF and tunneling-junction conductance = 1 μS.)