Single-electron device imitating reaction-diffusion systems

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Abstract

A promising area of research in electronics is the development of electrical systems that imitate the dynamics of life. To proceed toward this goal, we propose a single-electron device that imitates the behavior of the reaction-diffusion system, a chemical complex system producing dynamic, self-organizing phenomena in the natural world.

Reaction-diffusion system

The reaction diffusion system (R-D system) is a chemical system consisting of two or more chemicals in which chemical reaction and diffusion coexist under nonequilibrium conditions. It produces orderly spatiotemporal patterns of chemical concentration called the *dissipative structure*; two examples are shown in Figs. 1(a) and 1(b). Various RD systems exist in nature and produce a variety of dynamic, self-organizing phenomena. Developmental biologists have the opinion that life itself is a dissipative structure produced by the natural world, which is a large RD system in itself.

Constructing an electrical RD system with single-electron oscillators

The RD system can be considered an aggregate of chemical nonlinear oscillators, each of which is coupled with its neighbors through the diffusion of chemicals. To create an electrical analog of RD systems, we propose using single-electron oscillators instead of chemical ones. The action of diffusion in RD systems can be imitated by exploiting the waiting time for tunneling in single-electron circuits.

Figure 2(a) shows the configuration of the single-electron RD device we propose. The device consists of arranged single-electron oscillators coupled with one another through coupling capacitors C_L. A bias voltage (V_b or $-V_b$) is applied to each oscillator in such a way that its polarity is reversed between adjacent oscillators. Each oscillator (Fig. 2(b)) consists of a tunneling junction C_j and a multiple-tunneling junction C_m, a series of many tunneling junctions. The oscillator produces nonlinear oscillation at low temperatures because of the Coulomb blockade effect. It produces self-induced oscillation (Fig. 3(a)) when bias voltage V_b is larger than the threshold for electron tunneling in C_j. In contrast, it produces monostable oscillation (Fig. 3(b)) when V_b is smaller than the threshold. In a cycle of oscillation, the node voltage drops down to a negative because of an electron tunneling through C_j, then increases gradually owing to sequential electron tunnelings through multiple-tunneling junction C_m, and returns to its initial value after some transition time.

In this RD device, the electron tunneling in an oscillator changes the node potential of the oscillator. This induces tunnelings in adjacent oscillators, so tunneling is transmitted throughout the device. The tunneling transmission has a delay because of the waiting time for tunneling; this produces an effect analogous to diffusion in chemical RD systems. Consequently, electrical dissipative structure (spatiotemporal pattern of the node potential) is produced in the device.

Dissipative structure produced by the single-electron RD system---simulation results

We confirmed by computer simulation a variety of electrical dissipative structures produced in the device. Different device parameters produce different dissipative structures. Two examples are shown in Figs. 4(a) and 4(b). As shown in Fig. 4(a), the device produces a growing, rotating spiral pattern, which is the same behavior as that observed in the Belousov-Zhabotinsky chemical RD system and in a colony of the cellular slime mold. Figure 4(b) shows that the device also produces a segmenting, propagating nematode pattern; this self-reproduction phenomenon is similar to that observed in the Gray-Scott chemical RD system and in cell division. We are now developing this single-electron RD system into bio-inspired, information-processing devices.

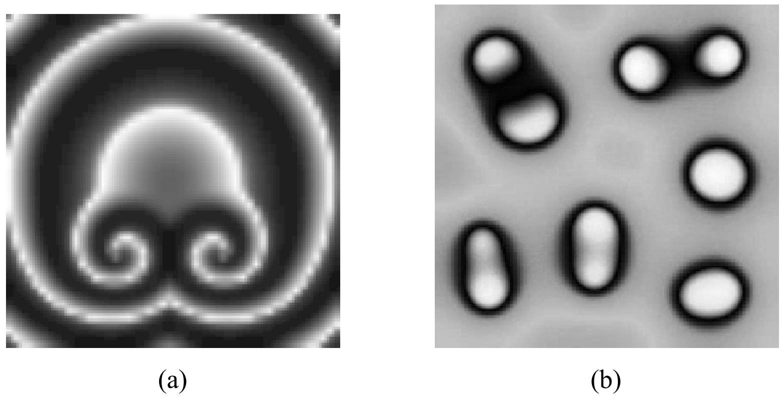

Fig. 1 Examples of the dissipative structure: (a) a growing, rotating spiral pattern produced by the Belousov-Zhabotinsky RD system and (b) a segmenting, propagating pattern produced by the Gray-Scott chemical RD system.

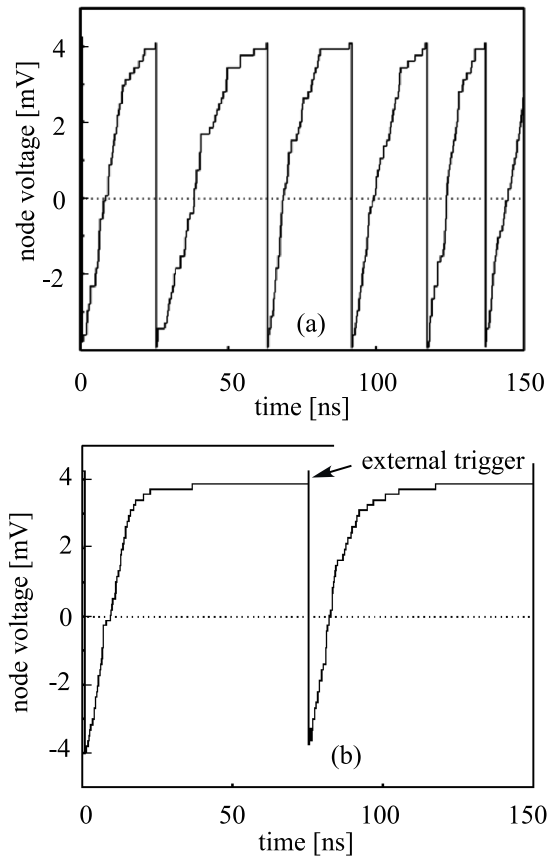

Fig. 3 Operation of the multiple-junction oscillator: (a) self-induced oscillation and (b) monostable oscillation simulated with a set of parameters: the capacitance of junction C_j = 10 aF, the tunneling conductance of C_j = 1 μS, the number of series junctions in C_m = 50, the capacitance of a junction in C_m = 500 aF, the tunneling conductance of C_m = 0.05 μS, V_b = 4.2 mV for the self-induced operation, and V_b = 3.8 mV for the monostable operation.

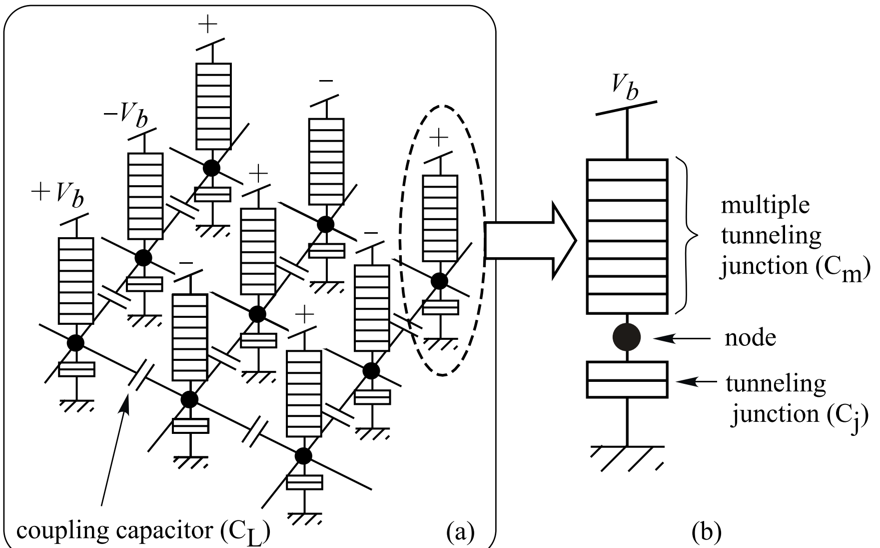

Fig. 2 Proposed single-electron RD device: (a) device configuration, and (b) a nonlinear oscillator consisting of a tunneling junction C_j and a multiple-tunneling junction C_m.

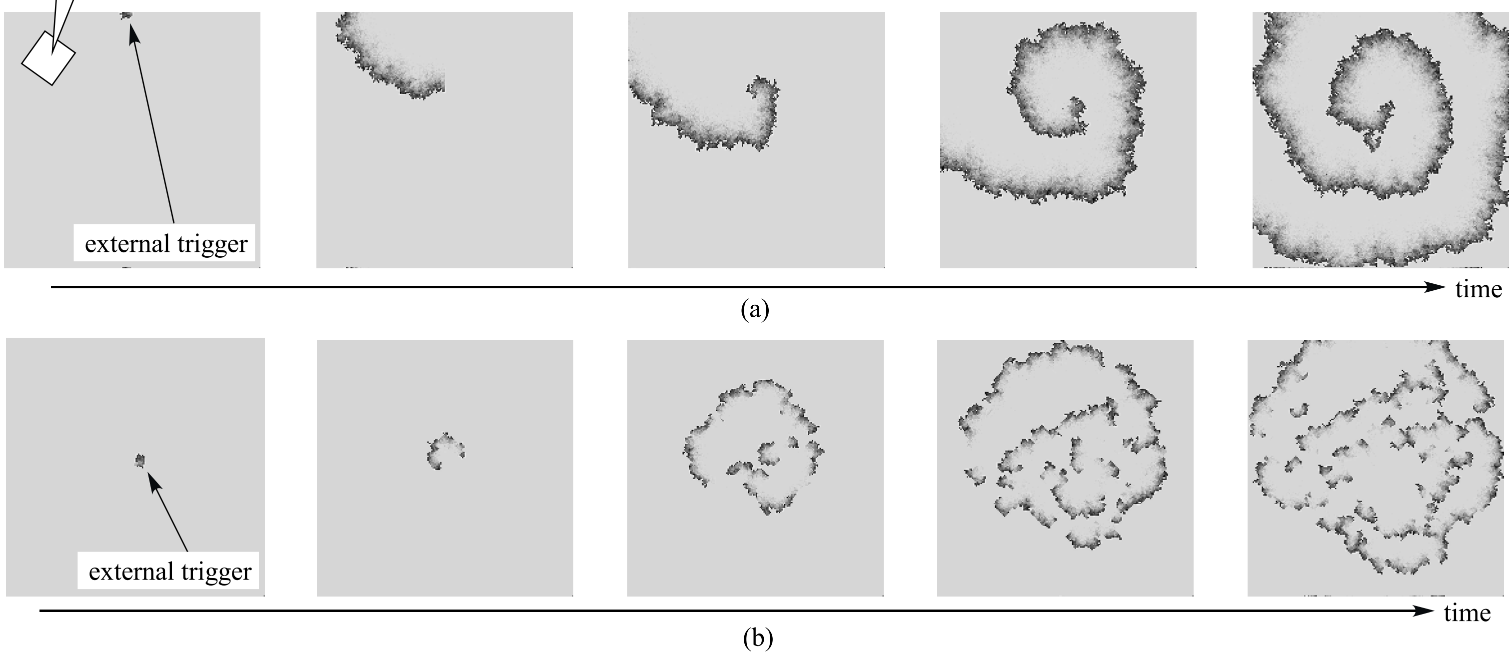

Fig. 4 Dissipative structures---spatiotemporal pattern of the node potential---produced by the single-electron RD device (simulation): (a) a growing, rotating spiral pattern, and (b) a segmenting, propagating nematode pattern. The patterns are represented with a grayscale: light shade means a high potential, and dark shade means a low potential. Parameter used are the same as in Fig. 3 except for the tunneling conductance of C_m and bias voltage V_b: the tunneling conductance = 0.5 μS, V_b = 9.9 mV for the spiral pattern and 9.7 mV for the nematode pattern. The capacitance of the coupling capacitor C_L = 2 aF.