Reaction-diffusion systems consisting of single-electron oscillators

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1. Introduction

A promising area of research in nanoelectronics 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, which is a chemical complex system producing dynamic, self-organizing phenomena in the natural world. Constructing an electrical analog of reaction-diffusion systems would enables us to generate artificial biodynamics on a LSI chip and develop bioinspired information-processing systems.

2. What is the reaction-diffusion system

The reaction-diffusion system (RD system) is a chemical complex system where chemical reactions and material diffusion coexist in a nonequilibrium state. It exhibits high-order nonlinear behavior and produces orderly spatiotemporal patterns of chemical concentration called *dissipative structures* (Fig. 1 and Ref.). There are various RD systems in nature, and a variety of dynamic, self-organizing natural phenomena can be explained using the concept of a dissipative structure. There are not a few biophysicists with the idea that life is a dissipative structure arising in the RD system we call earth.

3. Constructing electrical RD systems

An RD system can be considered an aggregate of coupled chemical, nonlinear oscillators. Each oscillator represents the local reaction of chemical substances and interacts with its neighbors through diffusion of substances. All oscillators correlate with one another and operate as an organic whole.

An electrical analog of RD systems can be created by using electrical oscillators instead of chemical ones and coupling these oscillators with one another in a way that imitates diffusion.

To construct a large-scale integration of nonlinear oscillators comparable with chemical RD systems, we propose using single-electron circuits as the oscillators. A single-electron circuit is an electronic circuit consisting of tunneling junctions and capacitors. It can easily generate nonlinear oscillation based on Coulomb blockade phenomenon, so it can effectively be used in producing small oscillators for electrical RD systems.

4. Single-electron RD systems

Figure 2 shows the three-dimensional and cross-sectional schematics for the single-electron RD system we are developing. Each oscillator consists of a quantum dot with four coupling arms, and there is a tunneling junction between the dot and the conductive substrate beneath it. Many series-connected junctions run between the dot and a positive-bias or a negative-bias electrode. Capacitive coupling between neighboring oscillators can be achieved by laying their coupling arms close to each other.

The variables in this system are the electrical potential of oscillator dots. Computer simulation revealed that the system produces electrical dissipative structures, i.e., orderly spatiotemporal patterns of dot potentials, under appropriate conditions. Figure 3 shows an example, a rotating spiral pattern of the dot potential generated in the system. With different sets of system parameters, the system produces a variety of animated dissipative structures that remind us of dynamics of life.

Reference

G. Nicolis and I. Prigogine, *Self-organization in nonequilibrium systems*, Wiley (1977).

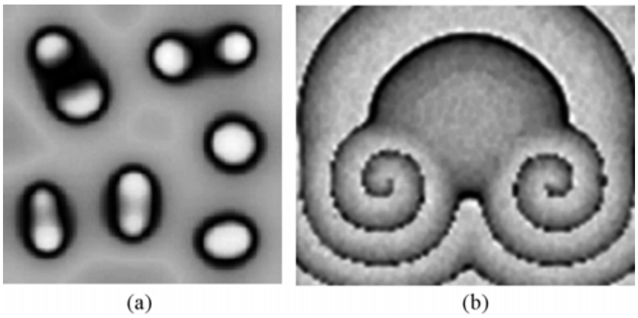

Fig. 1 Examples of dynamics in RD systems; chemical concentrations are expressed by shading in two-dimensional systems. (a) Self-duplicating pattern by Gray-Scott RD system, and (b) spiral pattern by Brusselator RD system.

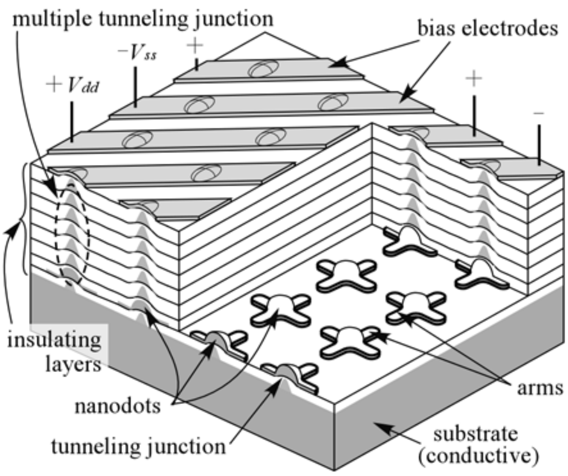

Fig. 2 Structure of the single-electron RD system.

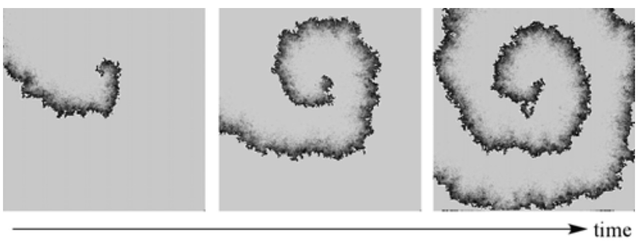

Fig. 3 Rotating, growing spiral pattern. Snapshots for three time steps. The potential of each oscillator dot is expressed by shading.