A single-electron oscillator with a multiple tunneling junction

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Abstract

We propose a single-electron nonlinear oscillator with a multiple tunneling junction. This oscillator consists only of tunnel junctions, and therefore, existing single-electron process technology can be used to make it. It is a suitable element for developing novel devices that implement biological information-processing architectures based on the nonlinear dynamics of coupled-oscillator systems.

Multiple-junction oscillator

The oscillator we propose is illustrated in Fig. 1(a). It consists of a minute dot (nanodot), a main tunneling junction Cj, and a multiple tunneling junction consisting of many tunneling junctions Cm connected in series. When connected to a bias voltage Vdd, the oscillator produces nonlinear oscillation at low temperatures, as illustrated later. Although a conventional SET oscillator, shown in Fig. 1(b), can produce similar oscillation, it is not easy to make because it requires a current-source resistor with a high resistance of gigaohms and a low parasitic capacitance of attofarads. In contrast, the oscillator we are proposing has no current source; therefore existing nano-process technology can easily be used to make it.

Operation of the oscillator

The oscillator operates at low temperatures at which the Coulomb blockade effect is established, and it produces an output voltage on the nanodot. The oscillator can be stable, astable, or monostable, depending on the value of voltage Vdd. At small positive values of Vdd, the oscillator is stable because no electron tunneling occurs, and it produces a constant positive output. In contrast, the oscillator is astable at high Vdd values because electrons tunnel continuously from the ground to Vdd through the nanodot; therefore it produces positive and negative outputs alternately.

At intermediate values of Vdd, the oscillator is monostable and produces one-shot operation triggered by an external pulse, as illustrated in Fig. 2 with a simulated result. In this condition, the oscillator is normally stable and produces a positive output. Upon application of a positive trigger pulse, an electron tunnels from the ground to the nanodot through the main tunneling junction; this makes the output drop to a negative (Fig. 2(a)). After triggering, the output starts to increase because the negative charge on the nanodot is neutralized by sequential electron tunnelings through a multiple tunneling junction (Fig. 2(b)). After some transition time, the oscillator returns to its initial state (Fig. 2(c)). The oscillator can also operate at negative bias voltages (the polarities of the trigger and the output are reversed). The parameter conditions for monostable operation are

$$N \gg 1, \quad Cm > Cj, \quad Rm \gg Rj, \quad \text{and} \quad (N(CjRj+CmRm) - CmRj)e/(2Cm(CjRj+CmRm)) < Vdd < Ne/(2Cm),$$

where N is the number of tunneling junctions in the multiple tunneling junction, Cm is the capacitance of the tunneling junctions, Rm is the tunneling resistance of the tunneling junctions, Cj is the capacitance of the main tunneling junction, Rj is the tunneling resistance of the main tunneling junction, e is the elementary charge, and Vdd is the bias voltage.

Operation of a coupled oscillator system---simulation results

To take steps toward creating novel devices, we designed a two-dimensional coupled-oscillator system as shown in Fig. 3. We coupled two kinds of monostable oscillators, i.e., an oscillator with a positive bias Vdd and one with a negative bias $-Vdd$, to make a unit cell, and arranged the cells on a plane. We then connected each oscillator with its neighbors by means of coupling capacitors Cd. In this system, electron tunneling in an oscillator changes the output of the oscillator and induces tunneling in neighboring oscillators. Therefore tunneling is transmitted (contagious) throughout the system.

We simulated the tunneling transmission by means of computer calculation. A result for a 10 x 10 cell array is illustrated in Fig. 4: the output voltages of positively biased oscillators are represented by the shade of cells so that dark shades indicate low voltages and light shades indicate high voltages. In this simulation, we applied a trigger pulse to the oscillator A in the upper left-hand corner of Fig. 4 to observe the tunneling transmission. Figure 5 shows the time dependence of the output voltage on five oscillators denoted as A, B, C, D, and E in Fig. 4. Tunneling was successfully transmitted throughout the system with a probabilistic delay. We are now developing this coupled-oscillator system into image-processing devices that make use of the tunneling transmission.

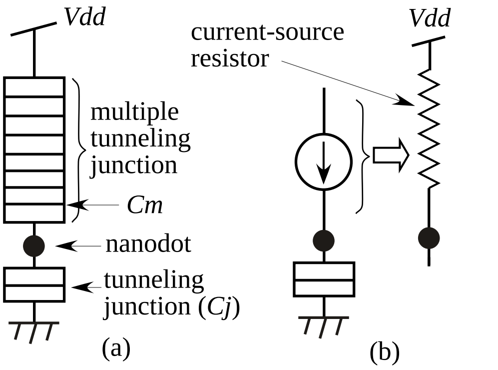

Fig. 1 Single-electron oscillator: (a) proposed structure with a multiple tunneling junction, and (b) conventional structure with a current source.

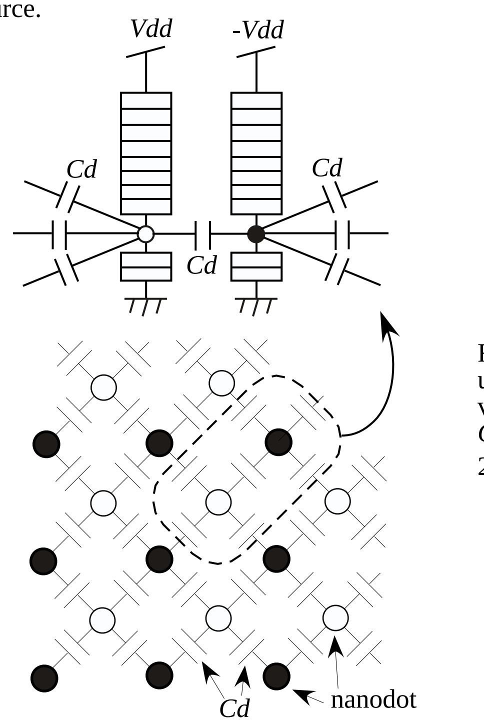

Fig. 3 Two-dimensional coupled-oscillator system consisting of positively biased oscillators (open circles) and negatively biased oscillators (closed circles) . Each oscillator is coupled with its neighbors by coupling capacitors *Cd*.

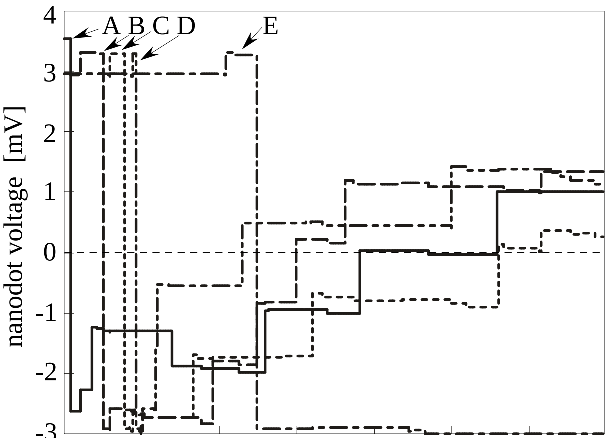

Fig. 5 Output voltage as a function of time, for the five oscillators denoted by A, B, C, D, and E in Fig. 4. Tunneling is transmitted throughout the system with a delay.

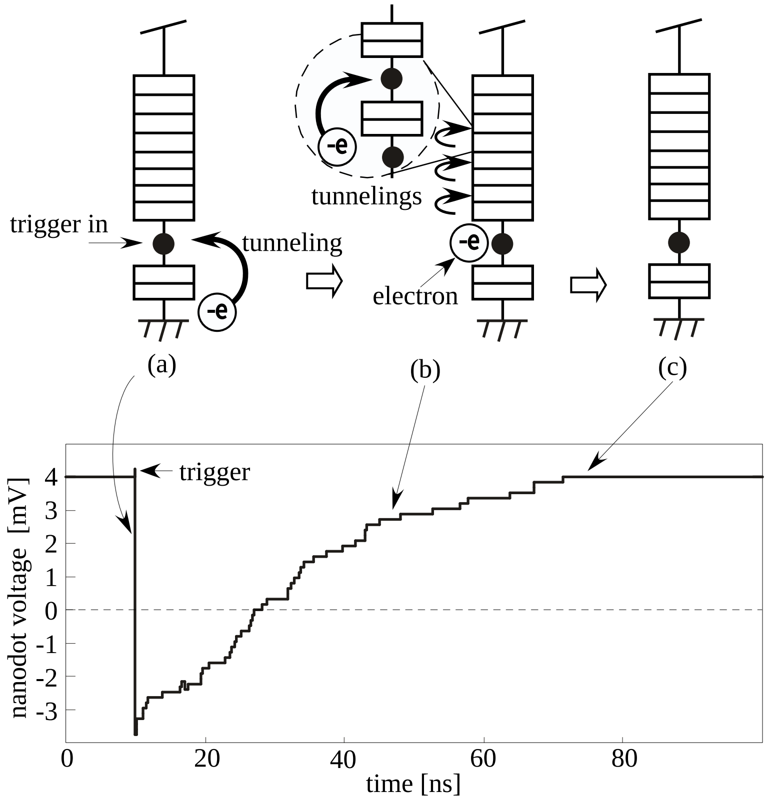

Fig. 2 One shot operation in the monostable oscillator. The upper figures show the transport of electrons. The lower figure shows the output voltage of the oscillator as a function of time, simulated with parameters *Cj* = 10 aF, *N* = 50, *Cm* = 500 aF, tunneling resistance of junction *Cm* = 20 MΩ, and tunneling resistance of junction *Cj* = 1 MΩ.

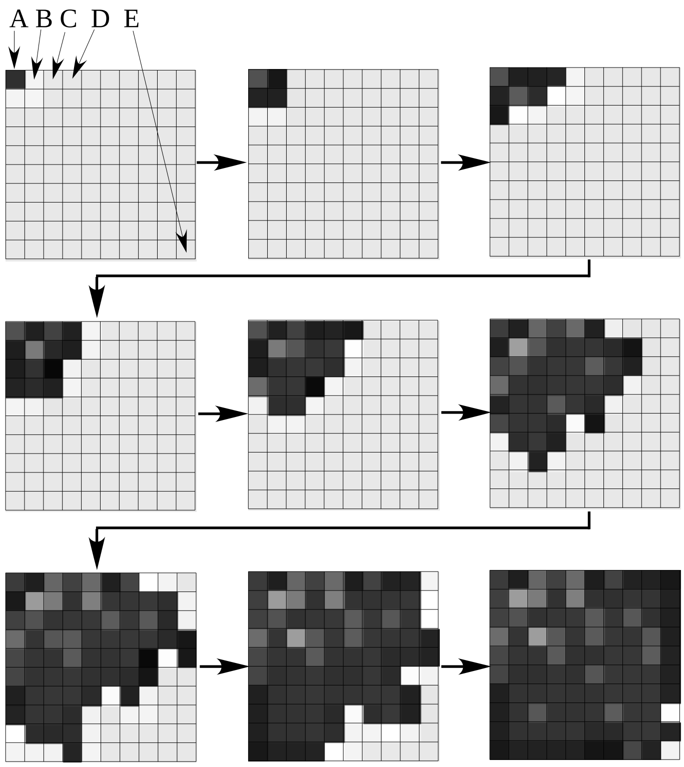

Fig. 4 Transmission of tunneling throughout the coupled-oscillator system. The output voltage of each positively biased oscillator is shown by the shade of the corresponding cells: a dark shade indicates a low voltage, and a light shade indicates a high voltage. Simulation parameters were *N* = 6, *Cj* = 10 aF, *Cm* = 60 aF, *Cd* = 2 aF, tunneling resistance of junction *Cm* = 300 MΩ, and tunneling resistance of junction *Cj* = 1 MΩ.