Analysis of Multi-Clocked Electron Pump Consisting of Single-Electron Transistors

Shuhei AMAKAWA[1]
and
Hiroshi MIZUTA[2] and Kazuo NAKAZATO[2]

[1]Microelectronics Research Centre, Cavendish Laboratory, Cambridge CB3 0HE, UK
Phone: +44-1223-337493, FAX: +44-1223-337706, e-mail: sa264@cam.ac.uk
[2]Hitachi Cambridge Laboratory, Cavendish Laboratory, Cambridge CB3 0HE, UK
Phone: +44-1223-442903, FAX: +44-1223-467942, e-mail: mizuta@phy.cam.ac.uk

ABSTRACT

Electron pump circuits consisting of single-electron transistors are analyzed in which electrons are pumped by multiphase clock pulses. An optimal low-temperature operation condition is presented where pumped current is maximized, yet the power consumption is not. Approximate formulae for the number of electrons transferred per clock cycle and the power consumption are derived for that condition, which show the advantage of the pump circuits for low-power applications. The power consumption becomes even less at higher temperatures. However, the relatively large island capacitance between transistors limits the operation temperature.

1. Introduction

Tsukagoshi *et al.* experimentally demonstrated the operation of electron pump circuits composed of multiple tunnel junctions (MTJs)[1, 2]. The MTJs were formed in side-gated δ-doped GaAs wiresand worked as single-electron transistors. The pump contains three or more MTJ transistors and is driven by unipolar multiphase clock pulses[2], as shown in Fig. 1. Tsukagoshi's pump involves two different capacitance scales. One is of the capacitances that constitute an MTJ transistor and the other is of the capacitances of clocking-gates. The clocking-gate capacitances $C_{\mathrm{G}i}$ are much larger than other capacitances in the pump. As a result, component MTJ transistors work virtually independently of one another as if being voltage-biased. The pumping operation reflects MTJ transistors' I-V characteristics rather than the precise charge configuration in the circuit. If one calculates the number of electrons transferred per cycle N_{c} from the net current I and the clock frequency f using the relationship $I = N_{\mathrm{c}}ef$, N_{c} is typically a few tens to several hundred. From a perspective of application, the multi-clocked pump is potentially useful as a building block of binary decision diagram logic circuits. Some experiments have already been conducted along the lines[3, 4]. However, the pump's charge transport mechanism and its possible performance have not been well understood yet. The purpose of this work is to analyze the operation of the pump circuit within the semiclassical model and to evaluate the power dissipation.

2 Model

We use the semiclassical theory of single-electron tunneling. The internal energy U of a circuit is given by the electrostatic energy stored at capacitors (including tunnel junctions):

$$U = \sum_{i \in \mathrm{cap}} \frac{Q_i^2}{2C_i}, \tag{1}$$

where Q_i and C_i are the stored charge and the capacitance, respectively. The electrical work done on a circuit by voltage sources is

$$W_{\mathrm{e}} = \sum_{j \in \mathrm{vsrc}} \int_0^t I_j(t') V_j(t')\,\mathrm{d}t', \tag{2}$$

where $V_j(t)$ is the output voltage of the jth voltage source and $I_j(t)$ is the current that flows through it. The energy supplied to a circuit will ultimately be transferred to the environment as heat, whatever the actual physical processes involved may be. Under the global rule of Coulomb blockade, the overall dissipation process is assumed to be fast enough. By the principle of conservation of energy, $dU = đW_e + đQ_{irrev}$, where, following the convention of thermodynamics, $đQ_{irrev} = \Delta F = F(t + \Delta t) - F(t)$ is, the heat added to the system within the time interval t and $t + \Delta t$. Here we have introduced an energy function $F = U - W_e$ using Eqs. (1) and (2). Thus, $-đQ_{irrev} = -\Delta F$ is the energy transferred to the environment, and $-\Delta F/\Delta t$ is the power dissipation. We evaluate the energy consumption using a cumulative total of ΔF for a simulation run. Evidently, it almost equals $-W_e$ over the long run.

As mentioned earlier, clocking-gate capacitances C_{Gi} are assumed to be sufficiently larger than other capacitances in the circuit. Each MTJ transistor, therefore, may be regarded as being voltage-biased with relevant island potential(s) ϕ_i and side-gate bias V_{gi}[5]. We approximate each MTJ transistor with a two-junction single-electron transistor as shown in Fig. 1(b). We further assume the pump to be uniform; that is, all transistors and C_{Gi} are the same. The effective isolation of component transistors enables us to analyze the pump circuit using the Coulomb blockade stability diagrams of each individual transistor. In the following, we mainly consider the four-transistor pump circuit shown in Fig. 1(b). The parameters used in our simulations are $C_1 = C_2 = 2\,\mathrm{aF}$, $C_g = 1\,\mathrm{aF}$, $C_0 = 0.5\,\mathrm{aF}$ [not drawn in Fig. 1(b)], $C_G = 100\,\mathrm{aF}$ and $R_T = 200\,\mathrm{k}\Omega$. With these parameters, the change in ϕ_i due to tunneling of a single electron is approximately[5] $\delta\phi \approx e/C_G \simeq 1.6\,\mathrm{mV}$ and sufficiently smaller than the other relevant voltage scale $e/C_\Sigma \simeq 29\,\mathrm{mV}$.

3 Results and discussion

We first focus on the electron pumping at the low temperature limit. When a clock voltage V_{pi} rises, the corresponding island voltage ϕ_i also rises and electrons flow onto the island. Note that in general electrons may flow onto the island through both transistors which are connected to it. Which transistor becomes conducting depends on the potential balance in the circuit. N_c is the *net* number of electrons transferred per clock cycle and not necessarily the number of electrons contained in a packet that would move along the pumpd. Electrons that flow in the reverse direction adversely affect the net current—that is, some electrons move back and forth within the pump without contributing to the net current while consuming energy. For the pumping to be efficient, electrons should flow in only one direction. One way to rectify the electron flow is to make the clock pulses appropriately overlap with each other as shown in Fig. 1(c). However, it is not the sufficient condition. One may achieve almost perfect rectification by properly choosing the side-gate biases of the "edge transistors" (TR1 and TR4) while setting all other side-gate biases to zero volts. A state of the pump can be represented by a point in the space spanned by all ϕ_i and V_{gi}. The pumping mechanism can be understood by considering the trajectory of the point. Figure 2 shows the steady trajectories for a set of well-chosen V_{g1} and V_{g4}, each of which also shows the corresponding transistor's stability rhomboid. In this condition, the trajectories in ϕ_i-ϕ_{i+1} planes are isosceles right-angled triangles, so that we will call it the "triangular condition." In this case, only one transistor is conducting at a time, which means that packets of N_c electrons are indeed conveyed in the pump.

The net current and the power are plotted as a function of V_{g1} in Fig. 3(a) and (b), respectively. The triangular condition occurs around the current maxima, where the power is not maximal. Although the power is not minimal in that condition, the net current flows only in the triangular condition when the clock amplitude V_p is small. One should therefore use the triangular condition and smaller V_p to reduce the power. Otherwise, the pump will consume extra energy in vain. The triangular condition also facilitates estimation of N_c and the power from the circuit parameters because tunneling events are localized to a particular transistor at each moment. By virtue of the perfect rectification, N_c equals the number of electrons which enter the pump through TR1. Therefore,

$$N_c \approx \{V_p - [\phi_1(\mathrm{A}) - \phi_1(\mathrm{D})]\}/\delta\phi, \tag{3}$$

which can be evaluated approximately from the circuit parameters. The simulation gives $N_c \simeq 45.4$, whereas Eq. (3) gives $N_c \simeq 46.7$, which is in good agreement with the simulation. The power consumption due to tunneling is given by

$$\begin{aligned} P &= f \times N_{\mathrm{c}} e \times \sum_{i} V_{\mathrm{diff}}^{(i)} \\ &= f N_{\mathrm{c}} e\{\phi_1(\mathrm{A}) + [\phi_2(\mathrm{D}) - \phi_1(\mathrm{D})] + [\phi_3(\mathrm{F}) - \phi_2(\mathrm{F})] - \phi_3(\mathrm{H})]\}, \end{aligned} \quad (4)$$

where $V_{\mathrm{diff}}^{(i)}$ is the voltage drop across the ith transistor when that is conducting. Thus we can estimate the power to be $P \simeq 0.6\,\mathrm{pW}$. The simulation result is also $P \simeq 0.6\,\mathrm{pW}$. The charge transfer mechanism in pumps with more transistors can be understood in the same way as the four-transistor pump. Steady trajectories in the ϕ_i-ϕ_{i+1} planes become triangles at almost the same edge-transistor side-gate biases as the four-transistor case, and the approximation method presented above is also applicable *mutatis mutandis*.

The main effect of non-zero temperature on the pump operation is to cause unwanted leakage current. At higher temperatures, the trajectories of a state point are no longer simple, and it is difficult to make good use of them. The side-gate biases of the edge transistors that give a maximal current tend to shift toward zero, i.e. the middle of stability rhomboids. The current is plotted in Fig. 4(a) as a function of $V_{\mathrm{g1}}(= -V_{\mathrm{g4}})$ for different temperatures. At higher temperatures, some energy is supplied from the environment, so that the power consumption decreases as expected, which is shown in Fig. 4(b). The two characteristic temperature scales involved in the pump are $e^2/2C_\Sigma k_{\mathrm{B}} \simeq 170\,\mathrm{K}$ and $e^2/2C_{\mathrm{G}} k_{\mathrm{B}} \simeq 9\,\mathrm{K}$. The highest operation temperature is determined not by the small island capacitance C_Σ of the MTJ transistors but by the comparatively large clocking-gate capacitance C_{G}. This is because the state point spends much of the time around near the stability border where the energy barrier for unwanted tunneling is of the order of $e\delta\phi$[5].

Too high a clock frequency f leads to missed tunneling events. After a state point has crossed a stability border, there is a finite time delay before tunneling takes place. The upper frequency limit f_{max} for vanishing temperatures can be roughly estimated to be $f_{\mathrm{max}} \approx e/8V_{\mathrm{p}} R_{\mathrm{T}} C_{\mathrm{G}}^2$. The numerical value for our simulation is $f_{\mathrm{max}} \approx 1 \times 10^8\,\mathrm{Hz}$, roughly above which the current does not increase linearly with f.

Because of the rather idealized model, our approximation method might be more useful as a means of estimating the best possible performance achievable by such pump circuits, rather than as a means of understanding the details of non-ideal, experimental results. The estimated operation temperature and frequency are not particularly high even with the relatively optimistic numerical values used in the simulations. The power consumption, on the other hand, is very low. This is because of the small number of electrons involved and the low operation voltage. If the entire circuit is scaled down, higher values of temperature and frequency would be achieved in theory. However, the scaling also means operation with accordingly higher voltages. Specifically, $V_{\mathrm{diff}}^{(i)}$ in Eq. (4), which reflect the size of the stability rhomboids, become larger. Consequently, the power consumption increases by the scaling if f and N_{c} are held constant. If the voltage and the frequency become comparable with those used in conventional circuits, the difference in power consumption would essentially arise from the difference in the amount of charge used, i.e. $N_{\mathrm{c}} e$ in Eq. (4).

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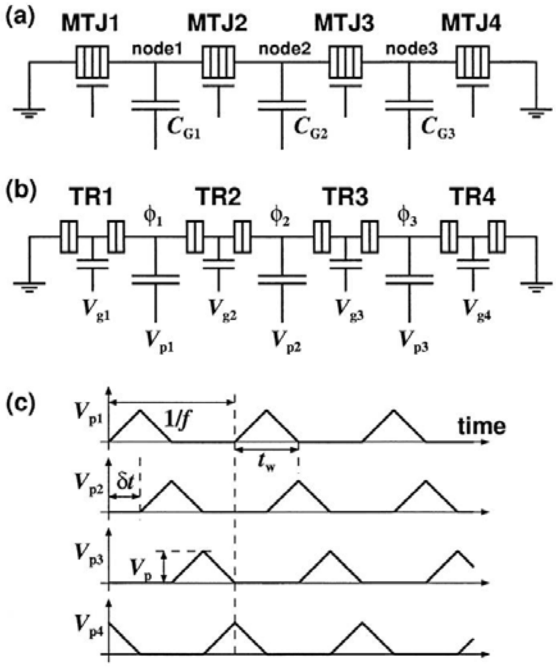

Figure 1: (a) Pump with four MTJ transistors. (b) Simpler model with two-junction transistors. (c) Triangular pulses are used to drive the pump. V_{p4} is used if a pump contains more than four MTJ transistors.

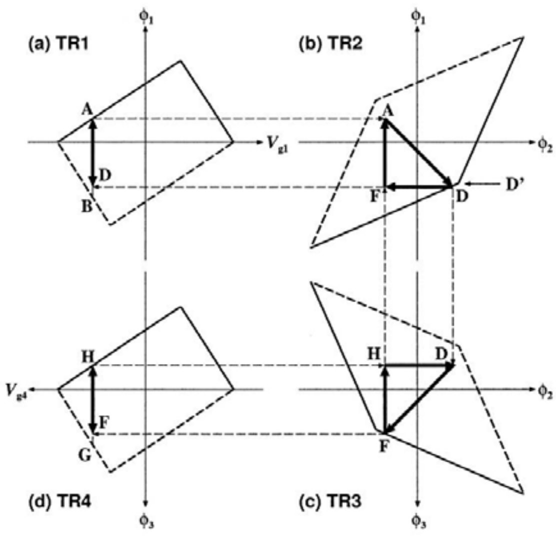

Figure 2: Stability rhomboids and steady trajectories in an optimal condition. The state point draws triangles in the ϕ_i-ϕ_{i+1} planes. Solid lines: forward-direction border. Broken lines: reverse-direction border.

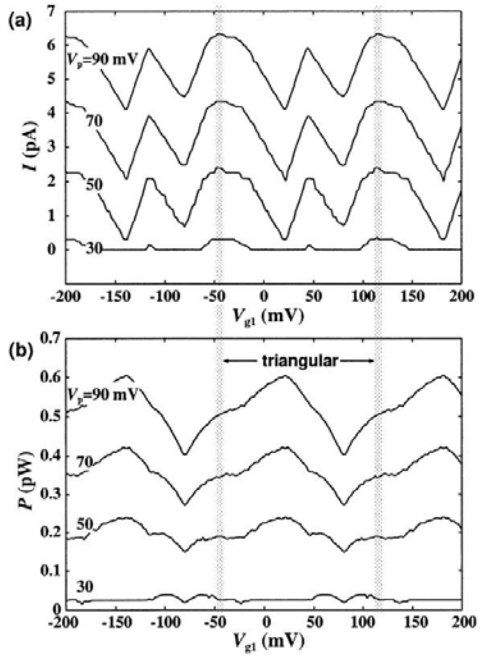

Figure 3: (a) Net current I and (b) power P as a function of V_{g1} for different values of clock amplitude V_p. The triangular condition occurs at around current maxima.

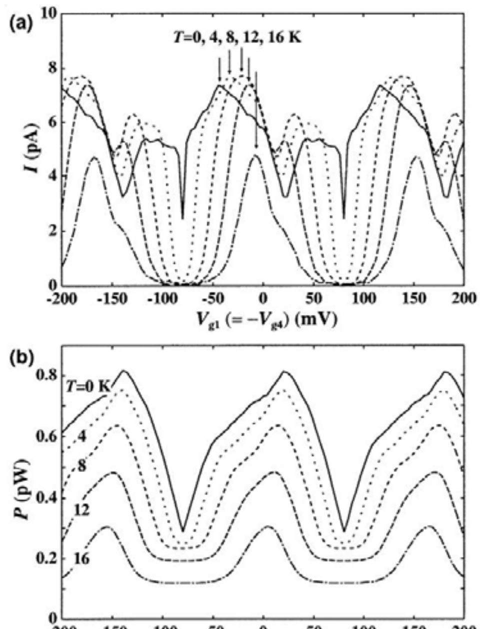

Figure 4: (a) Net current and (b) power versus $V_{g1} (= -V_{g4})$ for various temperatures. $V_p = 100\,\mathrm{mV}$ and $f = 1\,\mathrm{MHz}$.