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Implementation of Petri Net using Single-Electron Devices

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1. Introduction

Single-electron (SE) circuits can be viewed as the ultimate goal of future integrated circuits. Recent advances in SE devices (SEDs) have enabled the high-speed transfer and detection of SEs [1]. The discreteness nature of electron charge can lead to novel circuit architectures, like the SE binary-decision-diagram [2] and the SE fast adder [3]. This paper proposed an approach to compactly implement Petri net (PN) using SEDs.

2. Petri Nets

Petri net [4] is a widely used graphical method to describe concurrent distributed systems. Fig. 1(a) shows a representative PN that consists of *places*, *transitions*, and directed *arcs* among the places and transitions. Each place is marked with k tokens, denoted by its inner black dots. The system state is the configuration of all the token states in the places. A transition represents an event with its input and output places representing the pre-conditions and post-conditions of the event. The state of a PN is changed by events, according to the following firing rule. A transition t is *enabled* if each input places of t has at least $w(p,t)$ tokens, where $w(p,t)$ is the weight of the arc from p to t. A *firing* of an enabled transition removes $w(p,t)$ tokens from each input place p of t, and adds $w(t,p)$ tokens from each output place of t, where $w(t,p)$ is the weight of the arc from t to p. For example, in Fig. 1(a), because p_0 has 2 tokens, t_1 is enabled. After the firing of t_1, p_0 has 1 token, and p_1 has 1 token. After that, t_2 is enabled.

Hardware implementation of PN is quite hard [5] due to the concurrency nature of PN and, more specifically, the existence of *choice* (or *conflict*) and *place capacity* in PNs. Fig. 1(b) illustrates the case of *choice*. Only one of the two transitions t_1 and t_2 can fire, and which one will fire is non-deterministic. Fig. 1(c) explains the place capacity. The place p_0 has a limited capacity of 2. No more than 2 tokens can be put into the place.

3. Single-electron-device based Petri Nets

SEDs can compactly implement PNs for 3 reasons: 1) discrete electrons can directly represent *tokens*; 2) SE movements can directly correspond to the *event*; 3) the inherent stochastic behavior of SEs can well mimic non-deterministic PN events like *choice*. In SED-based PNs, places are mapped to electron storage node (SN), and tokens are mapped to individual electrons. The arcs are mapped to the SE turnstiles. Fig. 2(a) shows the SE turnstile consisting of nanowire MOSFETs. By applying pulses to the gates of the two FETs, electron can be accurately captured by the single-electron box (SEB) and then transferred. The transferred electron number N can be controlled by adjusting the coupling capacitance C_g, as shown in Fig. 2(b). N directly corresponds to the weight of the arc.

The firing rules of the transitions are realized by the multi-input logic gate consiting of single-electron transistors (SETs) [6] shown in Fig. 2(c). The two storage nodes are coupled to the gates of the two SETs. The SETs act as sensitive electrometer to readout the number of stored electrons N_1 and N_2. By adjusting the input capacitances of the SETs, the output voltage V_{out} is high only when both N_1=2 and N_2=1, as shown in the simulation result of Fig. 2(d). This function correspond to the firing rules shown in the inset of Fig. 2(c). The gate can be easily extended to more inputs.

Fig. 3 shows a fraction of PN and its corresponding SED circuits. Place p_1 has a capacity of 2. Place p_2 has a *choice* between t_1 and t_2. The output arcs and input arcs of p_0 and p_1 correspond to turnstiles *ts1*-*ts3* and *ts4*-*ts6*, respectively. The SEBs of *ts1* and *ts2* are coupled to the gates of t_1. The first gates of all turnstiles are controlled by a same voltage pulse V_p. The second gates of *ts1*, *ts2* and *ts7* are controlled by voltage pulse $V_{t1'}$, whose peak value is determined by the output voltage V_{t1} of t_1. The time sequences of V_p and $V_{t1'}$ are shown in Fig. 3(c).

Fig. 4 explains the operation principle of the circuit. The circuit state changes with the firing of events. The firing of an event has two phases. Initially, all gates are closed, two electrons retain in p_1, and one electron retains in p_2. The first phase determines which transitions will fire using the stochastic electron behavior, and the second phase executes the post-conditions of the transition. In *phase 1*, the first gates of the turnstile are first opened and then closed. With the rising of the barrier, Coulomb blockade is activated, and electrons are captured by the SEBs. The two electrons in p_1 are captured in the SEB of *ts1*. The electron in p_2 is captured in the SEB of *ts2* or in the SEB of *ts3*. This stochastic procedure corresponds to the *choice* of p_2. In the *first case*, electron in p_2 is captured by *ts2*, as shown in Fig. 4(b). After phase 1, V_{t1} is high because the firing pre-conditions are satisfied, and thus t_1 is enabled. V_{t2} is low and t_2 is disabled. In *phase 2*, a positive voltage pulse $V_{t1'}$ is applied to the second gate of *ts1*, *ts2* and *ts7*, since V_{t1} is high. The electrons in the SEBs of *ts1* and *ts2* flow to the source, and *ts7* transfer an electron into p_3 (not shown in Fig. 4), according to the firing rule of t_1. A negative voltage pulse $V_{t2'}$ is applied to *ts3*, since V_{t2} is low. The place capacity of p_2 is realized by adjusting the capacitance of the SN. In phase 2, *ts4* injects 2 electrons into p_1. The potential of p_1 is then decreased to be lower than the SEB of *ts3*, so that the electron captured by *ts3* is blocked from enter into p_1. In the *second case*, electron in p_2 is captured by *ts3*, as shown in Fig. 4(c). After phase 1, t_1 is disabled and t_2 is enabled. In phase 2, t_2 fires and the electron in *ts3* flows to the source. Since t_1 is disabled, a negative pulse of $V_{t1'}$ is applied to *ts1* and *ts2*. In this case, *ts1* and *ts2* act as SE ratchets [1] and the two electrons in the SEB of *ts2* is transferred back to p_1, due to the cross capacitance between the gate and the SEB. As a result, the electron transfers of *ts4* and *ts5* are blocked. In summary, the *firing rules*, *choice* and *place capacity* of PNs are simply realized using the nature of electrons.

The SED-based simple PN can be extended to *timed* PN and *stochastic* PN, which is currently under investigation. Fig. 5 briefly illustrates the basic idea. The exponential distributed *fire rate* can be mapped to the electron tunneling/capture rate and can thus be controlled by the gate voltages of the SE turnstiles.

4. Conclusion

The PN in Fig. 1(a) was simulated using HSPICE. The SE turnstile was described by a behavioral model [3]. Correct operation was demonstrated. The SED-based PN has simple structure and low power dissipation, which makes it promising as future parallel controllers. It may also be useful for quickly obtaining the *coverability* properties of large size PNs.

References

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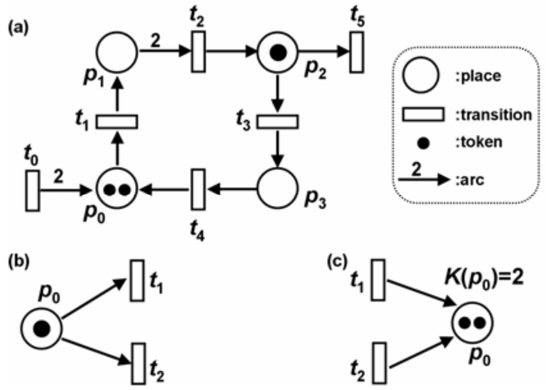

Fig. 1. (a) An illustration of the Petri net. (b) A Petri-net structure called a *conflict* or *choice*. (c) A Petri-net place with a *limited capacity*.

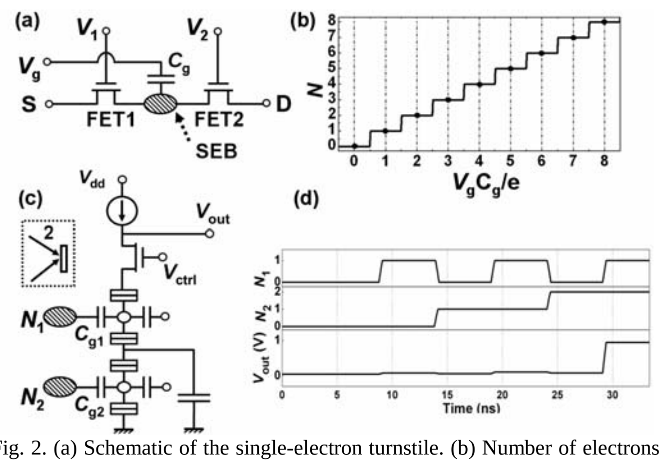

Fig. 2. (a) Schematic of the single-electron turnstile. (b) Number of electrons transferred per cycle as a function of V_gC_g/e, where C_g is the coupling capacitance between the SEB and the upper gate. (c) Schematic of the SE multi-valued logic gate and (d) its simulation results. V_{out} is high only when both N_1=2 and N_2=1. C_{g1}=0.16aF, C_{g2}=0.32aF, $R_{s,d}$=200K, $C_{s,d}$=0.32aF.

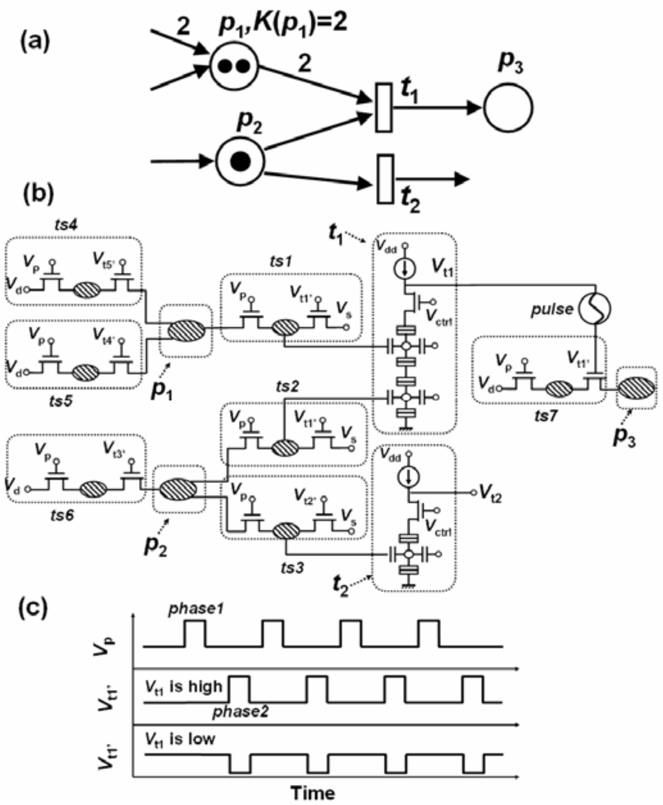

Fig. 3. (a) A illustrative Petri net and (b) its SED circuit schematic (c) Time sequence of V_p and $V_{t1'}$. The peak value of $V_{t1'}$ depends on V_{t1}.

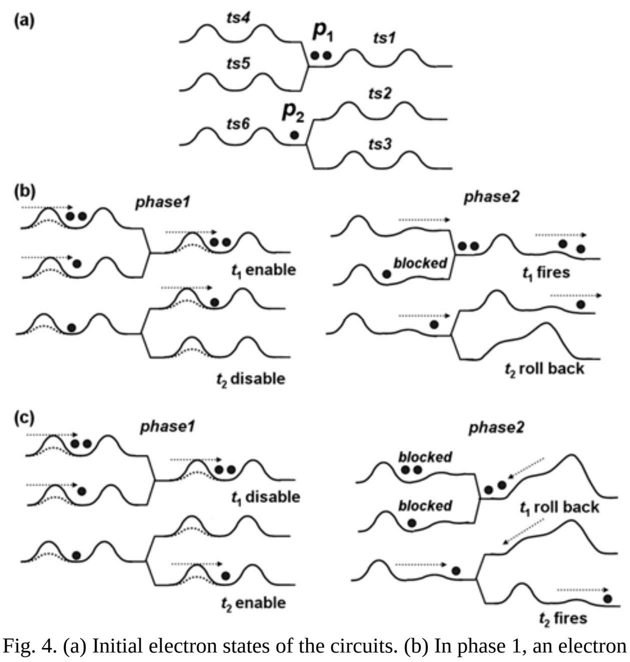

Fig. 4. (a) Initial electron states of the circuits. (b) In phase 1, an electron is captured by *ts2*. In phase 2 t_1 fires. (c) In phase 1, an electron is captured by *ts3*. In phase 2, t_2 fires and the 2 electrons captured by *ts1* is transferred back to p_1.

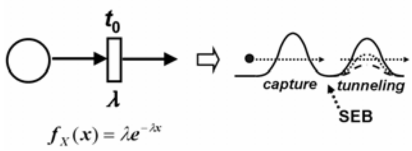

Fig. 5. Schematic of a stochastic *transition* and its possible SED implementation. The electron capture probability of the SE turnstile is determined by the upper gate voltage. The tunneling rate is determined by the barrier shape.