Building Blocks for Fluctuation Based Calculation in Single Electron Tunneling Technology

Saleh Safiruddin and Sorin Cotofana, Senior Member IEEE
Computer Engineering Laboratory
Delft University of Technology, Delft, The Netherlands

Ferdinand Peper, Member IEEE
Nano ICT Group
National Institute of Information and Communications Technology, Kobe, Japan

Jia Lee
Celartem Technology Inc., Tokyo, Japan

Abstract—**Fluctuations and noise are important factors interfering with the operation of devices and circuits, and this effect will become stronger as feature sizes decrease. This paper presents two building blocks for Single Electron Tunneling (SET) circuits that are designed with signal fluctuations in mind. One of these blocks, a so-called *Hub*, outputs its signals to other building blocks by repeatedly offering its signals at its output terminals, and taking them back when they cannot be delivered. Based on a random scheme of signaling, the Hub requires fluctuations to drive its operation. The other building block, a *Conservative Join*, is designed to work in cooperation with the Hub, though it does not require fluctuations. We propose SET circuit topologies for both blocks, and analyze their behavior at a temperature of 1K by computer simulations with SIMON 2.0. The two very different modes of operation in the blocks—fluctuation vs. non-fluctuating—can be accommodated by appropriately tuning circuit parameters, as we show. Utilizing these proposed topologies we then present an example of a network constructed using the two building blocks.**

I. INTRODUCTION

The expectation that current semiconductor technologies (CMOS) cannot be pushed beyond certain limits especially with regard to power consumption and scalability, has motivated intensive research into a wide variety of alternatives. Single Electron Tunneling (SET) technology has attracted interest in this context due to its potential for extremely low power consumption. Based on the tunneling of electrons through junctions, SET differs fundamentally from CMOS, and opens up avenues for new computational paradigms.

In the last few years there has been considerable interest in researching methods to effectively utilize the basic SET properties. Such efforts include [1], [2], [3], [4], [5], which are based on Single Electron Encoded Logic and Electron Counting concepts. Theoretical results on the area and delay complexity of arithmetic operations using those new paradigms indicate great potential. However, one of the most important challenges for implementing circuits based on quantum tunneling thus far has been the stochastic nature of the tunneling process. Tunneling through a junction becomes possible when the junction's actual voltage V_j exceeds the junction's critical voltage $V_c = \frac{q_e}{2(C_j+C_e)}$, where $q_e = 1.602 \cdot 10^{-19}C$, the capacitance of the junction is C_j, and the capacitance of the remainder of the circuit as seen from the junction is C_e. The delay of such circuits cannot be analyzed in the traditional sense. Instead, for each transported electron one can describe the switching delay as $t_d = \frac{-\log P_{\text{Error}} R_t}{|V_j|-V_c}$, where R_t is the junction resistance and P_{Error} is the probability that the desired charge transport has not occurred after t_d seconds. This probabilistic delay complicates the direct utilization of SET-based computation in building synchronously timed arithmetic units and since the exact tunnel time of an electron is not known, extensive error correcting schemes are required and switching times have to be lengthy. This has motivated research for SET architectures and circuits based on delay-insensitive computations so that the problems arising from unknown delays are eliminated altogether [6].

Another proposal has attempted to turn one of the weak points of SET technology — sensitivity to noise and fluctuations — into an asset, by employing it actively in a simulated annealing scheme in Boltzman machines [7]. SET technology is especially suited for implementing the token-based nature of this architecture, with tokens representing electrons or vacancies of electrons. Being focused on implementations of neural networks, however, this effort has found no follow-up in the context of traditional arithmetic circuits.

This paper investigates the potential use of fluctuations in the operation of arithmetic circuits implemented by SET technology. It does so by presenting two building blocks for Single Electron Tunneling (SET) circuits that are designed with signal fluctuations in mind. One of these blocks, a so-called *Hub*, outputs its signals to other building blocks by repeatedly offering its signals at its output terminals, and taking them back when they cannot be delivered. Based on a random scheme of signaling, the Hub requires fluctuations to drive its operation. The other building block, the *Conservative Join*, is designed to work in cooperation with the Hub, though it does not require fluctuations. The two building blocks have been shown to form a computationally universal set from

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which any desired functionality can be constructed [8].

II. BUILDING BLOCKS

The two building blocks used in this paper have been proposed in the context of so-called *Brownian circuits* [8], [9]. The idea of Brownian circuits is to use fluctuations to guide signals through a circuit. That is, fluctuations drive a search process through a Brownian maze formed by the topology of the circuit [9].

The first building block is the *Hub*, which contains three wires that are bidirectional (Fig. 1). There will be at most one signal at a time on any of the Hub's wires, and this signal can move to any of the wires due to its fluctuations.

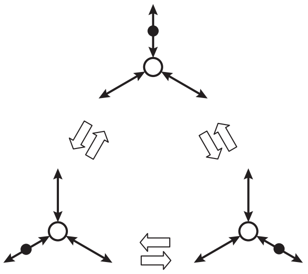

Fig. 1. Hub transitions. Fluctuations cause a signal to move between any of the Hub's three wires in any order.

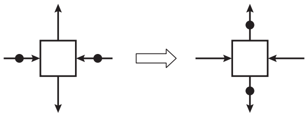

Fig. 2. CJoin transition. If there is a signal on only one input wire, this signal remains pending until a signal arrives on the other wire. These two signals will then result in one signal on each of the two output wires.

The second building block is the *Conservative Join (CJoin)*, which has two input wires and two output wires (Fig. 2). The CJoin can be interpreted as a synchronizer of two signals passing through it. Signals may fluctuate on the input wires of a CJoin, but once processed by the CJoin, they will be placed on the output wires and there is no way back, even though fluctuations on the output wires are allowed. When connecting CJoins to each other, we should make sure that input terminals face output terminals. Hubs, having bi-directional wires, may be connected in any way to CJoins or other Hubs.

III. IMPLEMENTATIONS

To calculate circuit parameters for each proposed circuit topology which would lead to the desired functionality, we start with general conditions which have to be met to enable single electron manipulations. There are two major effects which have to be considered, namely quantum fluctuations and thermal energy. If either of these two effects is dominant then the electrons are not localized on islands and the desired functionality cannot be achieved.

Since electron tunneling is a quantum mechanical process, an electron's wave function extends through potential barriers, and the electron is spread over the islands in a SET circuit. If this effect was to prevail there would be no localized charges and computations using electrons would not be possible. To ensure that the charge of an electron is quantized on each specific island the tunnel junctions must have a sufficiently high tunneling resistance, so that the charging energy, also called the Coulomb energy, dominates over the quantum charge fluctuations. This can be expressed as:

$$\frac{{q_e}^2}{2 \cdot C_j} \cdot R_j \cdot C_j >> h => R_j >> h/{q_e}^2 = 25.8k\Omega$$

where h is Planck's constant, C_j is the tunnel capacitance, and R_j is the tunneling resistance. Therefore, the resistance of all the tunneling junctions in the following implementations is chosen as 100kΩ, which has also been used in previous studies, [1], [2], [3], [4], [5].

The second effect that has to be considered is that of thermal energy. If the thermal energy dominates over the charging energy, E_c, the quantization effects become again non-observable. The condition is then $E_c = \frac{{q_e}^2}{2 \cdot C} > k_B \cdot T$, where k_B is Boltzmann's constant and T is the absolute temperature. The capacitance of an island should therefore not exceed $926aF$ for a temperature of $1K$.

The temperature of $1K$ was chosen to demonstrate the coexistence of fluctations of quantized electron charges and deterministic behaviour in a circuit. As was previously mentioned, the thermal energy should not dominate the circuit elements, however, to achieve the desired Hub functionality, there should be enough thermal energy flucutations to enable electrons to tunnel from one island to another. This was achieved by bringing the voltages over certain tunneling junctions close enough to their critical voltages such that an increase in the energy of an electron at the junction due to the extra thermal energy would at random moments cause the electron to tunnel forward, and when the thermal energy decreases to tunnel back again. The thermal energy is thus effectively used as a random control voltage. The CJoin has to have a deterministic response thus it has to be designed in such a way that the thermal energy has little or no effect on its behavior. The design of the CJoin is based on the buffering techniques introduced in [2].

When a tunnel junction appears in the figure it is designated with a "J" and a number, and when the circuit parameters are described the capacitance of the tunnel junction is referred to with a "C" and the same number. The source voltage Vs is set at 16mV to coincide with previous research. All simulations were done using SIMON 2.0 software [10].

Figure 3 presents a SET circuit topology that exhibits the Hub functionality. The circuit was simulated at $1K$. The circuit parameters are as follows: $Cs1 = 10aF; Cs2 = 0.5aF; Cs3 = 0.2aF; Cg = 10aF; C1 = C3 = C5 = 10aF; C2 = C4 = C6 = 0.1aF$.

The circuit operates as follows. When Va is high an electron travels away from $n1$ through $J2$ and $J1$. Once there is a vacancy on $n1$, one of the two SET transistors, $J3 - J4$ or $J5 - J6$ supplies an electron to node $n1$, from $n2$ and $n3$, respectively. However, $Cs3$ is chosen with a low value such that the thermal energy of the electron is sometimes enough to overcome the voltage differences and the electron tunnels back into $n2$ or $n3$. The charge thus jumps from $n1$ to $n2$ or $n3$ and then back into $n1$ and then again randomly into $n2$ or $n3$.

The results of the simulation can be seen in Figure 4. The circuit is stable when there is no supply of a charge. After time step 0.1, when the charge is supplied, we can see a random travelling of the charge through nodes $n2$ and $n3$, via $n1$.

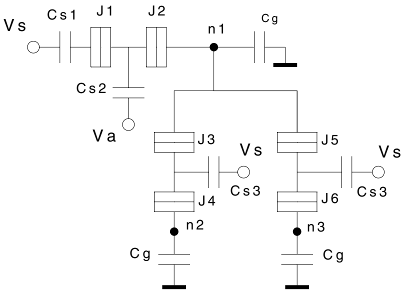

Fig. 3. Hub circuit implementation

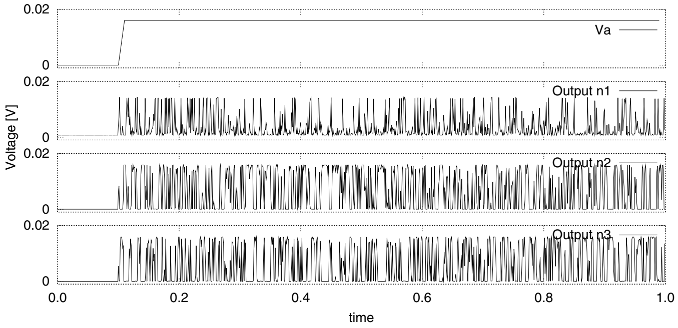

Fig. 4. Hub circuit simulation results

Figure 5 presents a SET circuit topology that implements the Conservative Join. The circuit was simulated at $1K$. The circuit parameters are as follows: $Ca = Cb = 1aF; Cs1 = Cg1 = 10aF; Cs2 = Cn3 = 0.5aF; Cn1 = 0.25aF; Cn2 = 0.3aF; Cg2 = 11.5aF; Cg3 = 10.5aF; Cg4 = 11aF; C1 = C3 = C5 = C7 = C11 = 10aF; C9 = C14 = 5aF; C2 = C4 = C6 = C8 = C10 = C12 = C13 = 0.01aF$.

The circuit operates as follows. When inputs Va and Vb go high, electrons tunnel through the junctions $J1-J2$ and $J5-J6$ leaving positive charges on nodes $n1$ and $n3$, respectively. When $n1$ and $n3$ simultaneously have a charge, an electron tunnels from node $n5$ into the source through junctions $J9$ and $J10$. Subsequently, an electron tunnels from $n6$ to $n5$ due to the SET transistor $J11 - J12$, which acts as a buffer and seperates the influences of the input $Cn1$ gate capacitors and the $Cn2$ driving gate capacitors. Now the charge on node $n6$ causes the charge on $n1$ to be transferred into $n2$ through $J3$ and $J4$ and the charge on $n3$ to be tranferred into $n4$ through $J7$ and $J8$. Nodes $n2$ and $n4$ are the output nodes and the input tokens, represented as positive charges, are thus transferred to the output. To bring the circuit back to a reusable state, the charge remaining on $n6$ has to be removed. This is achieved by connecting $n6$ to ground via a reversed transistor structure, $J14 - J13$. If there is a positive charge residing on $n6$ and the charges on $n1$ and $n3$ become zero an electron tunnels from ground into $n6$, resetting the circuit. Once the output charges on $n2$ and $n4$ have been consumed the circuit is then ready to accept new input tokens.

The results of the simulation can be seen in Figure 6. Charges appear on the output nodes $n2$ and $n4$ only when both Va and Vb go high, but not when only one of them goes high.

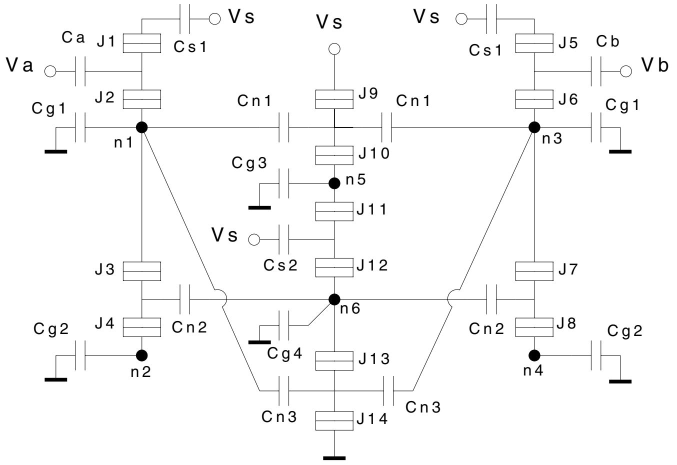

Fig. 5. Conservative Join circuit implemenation

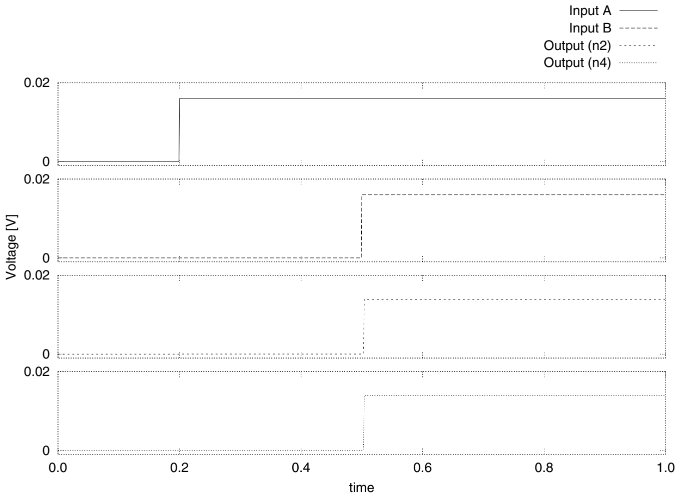

Fig. 6. Conservative Join circuit simulation results

IV. NETWORKS OF FLUCTUATION BASED CIRCUITS

Even though the two circuit topologies function as required at the same temperature, simply connecting them results in feedback, and to retain the random fluctuations in the Hub certain parameters have to be adjusted. The circuit parameters of the Hub that have to be adjusted are $Cs2$, $Cs3$, $C2$, $C4$, and $C6$. $Cs2$ and $Cs3$ have to be changed to $0.7aF$ and $C2$, $C4$, and $C6$ have to be changed to $0.01aF$. Also, the grounded capacitance Cg, corresponding to the unconnected node of a Hub ($n2$ or $n3$) has to be changed to $10.4aF$. The circuit parameters of the CJoin remain unchanged.

To demonstrate that these building blocks can be combined into one functional circuit we use an example network of two

CJoins and three Hubs (Figure 7), with one Hub connected to both CJoins. With signals present on all Hubs it is a matter of chance as to whether it is the first CJoin that fires or the second one. The common token (at the center) is consumed by the firing CJoin, leaving the other (non-firing) CJoin with only one token. A number of simulations were done using different random generator seeds and the results of two of these simulations are presented in Figures 8 and 9. In both simulations outputs which remain '0' are left out. Fig. 8 shows the charge distributions on A and B (corresponding to the left Hub) and C and D (right Hub); we see fluctuations on both Hubs. The central Hub is not supplied with a token until time 0.5 and at this point the CJoin with outputs E and F fires and the charges are trapped at its output. Figure 9 shows similar behaviour in the second simulation, except that now the CJoin with output G and H fires, trapping the charges at its respective outputs.

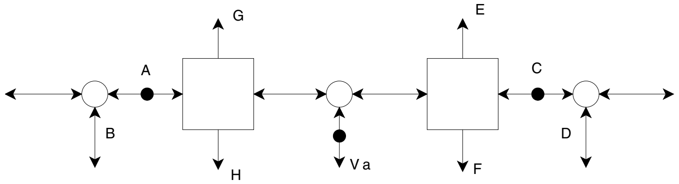

Fig. 7. Conservative Joins with Hubs Network Example

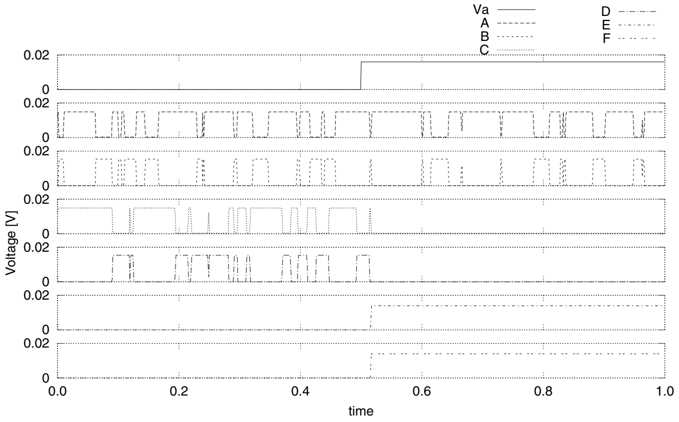

Fig. 8. Conservative Joins with Hubs simulation 1

V. CONCLUSION

We have demonstrated that the Conservative Join and the Hub can be implemented in SET technology and can coexist at the same temperature (1 Kelvin in this case) while maintaining their desired behaviors. These two blocks constitute the foundation of building Brownian SET based circuits, which is a computation paradigm able to turn the unpredictable SET behavior into an useful feature. Due to the nature of the thermal fluctuations there is a robustness issue, in that a thermal spike may cause the Conservative Join to malfunction. This could be dealt with by adjusting the parameters of the Conservative Join so as to make it less sensitive to random thermal spikes. This, however, might require the Hub part to contend with a lower relative thermal control voltage, and would lead to a slower switching of electron charges. Thus a trade-off may have to be made between robustness and speed, though the charge fluctuations rate is high enough not to degrade the overall performance.

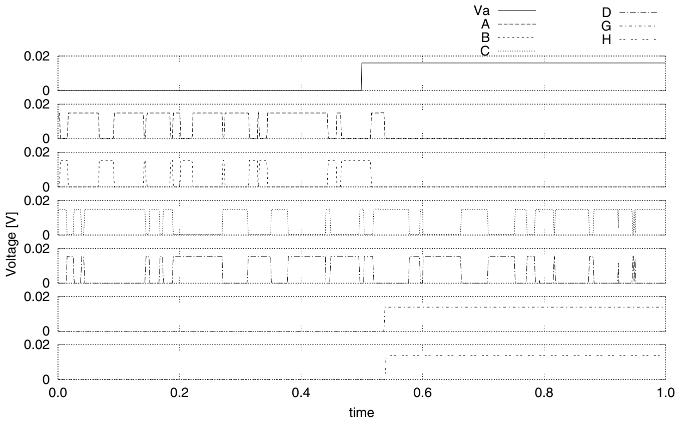

Fig. 9. Conservative Joins with Hubs simulation 2

It has been shown in this paper that SET technology is very suitable for implementing fluctuation-based calculations. The proposed architecture has the potential to reduce the strain on the fabrication technology by relaxing the constraints on the allowed thermal energy, and it allows implementations that are efficient and straightforward. Moreover, the delay-insensitive nature of the operations and the robustness to errors are reducing the demands on the technology, underlining the promises of the proposed avenue.

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