Ultra Low Power/Energy SET-based Axon-inspired Communication

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Abstract—Power consumption has been recognized as a grand challenge for nano-electronics. With continuous scaling, wires (much more than devices) are going to be the ones (almost entirely) determining dynamic power. That is why innovations in classical (i.e., based-on-wires) communication as well as radical (i.e., beyond-wire) solutions are called upon to tackle this challenge. One source of inspiration is expected to be the brain, and in particular the neurons themselves as they are able to communicate at reasonably large distances (compared to their size) on a very limited power budget (dendritic and axonal communications). This paper builds on very recent results analyzing axon-inspired communications as dense lattices of locally connected ion channels. In this paper we try to emulate the logical functioning of a voltage-gated ion channel using single-electron technology/transistors (SETs). Such an approach should in principle lead to practical power/energy lower bounds for nano-electronics.

Index Terms—Communication, axon, ion channel, power, single electron technology/transistor (SET).

I. INTRODUCTION

If the current trend of transistor miniaturization continues, it is expected to hit roadblocks. Currently, scaling MOSFET is hampered by: (1) high electric fields; (2) non-uniform doping; (3) leakage; and (4) performance degradations due to interconnects/wires [1]. In this paper the focus is on interconnects/wires for reducing/limiting dynamic power/energy (i.e., charging and discharging the wires) while maintaining reliable communications (on such wires). This is a major challenge for future nano-circuits as in the next few years it is expected that 80% of microprocessor power will be consumed by interconnects [2].

We start from axonal communication [3] and from results explaining the functioning of “locally connected” voltage-gated ion channels [4]. For nano-electronics, SET is considered the ultimate low-power technology [5]. That is why we have used SETs to build the blocks emulating ion channels. In fact, we will use SET gates to emulate the functioning of voltage-gated ion channels, and try to estimate the power consumption. Conclusions and further directions of research are ending this paper.

II. AXONAL COMMUNICATION

In the early 1950’s [3], scientists were starting to understand the propagation of the action potential (see Fig. 1, upper part) as the basis for the propagation of nerve impulses. That theory became a cornerstone of cellular biophysics, and set an entire field of scientists to work on excitable membranes.

Fig. 1. (a) The structure of a neuron (Source: http://www.mhhe.com/biosci/esp/2001_esbio/folder_structure/an/m2/s4/assets/images/anm2s4_1.jpg).
(b) Action potential being orchestrated by many ion channels.
ions is higher outside the neuron, while the concentration of K⁺ ions is higher inside the neuron. Na⁺ and K⁺ pumps are responsible for maintaining the ion concentrations. The ion channels are normally closed most of the time and open only for very brief moments. The gating, i.e., opening of these channels occurs due to signaling molecules (ligand), mechanical deformations, voltage, and light.

The current understanding of axonal communication is that it relies almost entirely on the dense locally connected arrays of voltage-gated ion channels. These are pore-forming proteins (or an assembly of several proteins) present in the membranes (lipid bilayer) of all biological cells. When voltage-gated Na⁺ ion channels open, the ions start flowing into the cell. This causes an increase in local potential, which in turn activates a neighboring Na⁺ channel to open. The localized depolarization of the membrane makes the nearby voltage-gated K⁺ to also open. The K⁺ ions start flowing out of the cell, causing repolarization. Closing of both types of channels happens automatically after a brief period of time.

Very recent results have suggested that locally-connected arrays are key for communication [6] and computations [4].

III. SET State-of-the-Art

SETs are quantum-based devices relying on Coulomb blockade [5]. Current research has looked into logic gates built from SETs, but there has been limited work on investigating the power/energy characteristics of such devices [7], [8], and even less when going to the circuit/system levels [9], [10].

With respect to simulations, Lientschnig et al. [11] have proposed SPICE models for hybrid SETs/FETs. They have determined average currents through SETs as a function of the gate and bias voltages as well as temperature. In [12],

Fig. 3. SET-based OR-2 as a NOR-2 followed by an INV.

Fig. 4. OR-2 inputs U2 and U3, and the corresponding output U1. Six input vectors appear at 10ms intervals.

Fig. 5. Plots of OR-2 input U2 (blue) and output U1 (red).

Fig. 6. OR-2 power and PDP (energy) for the test sequence.
Waser has detailed different models for source tunneling junctions and SET-based pull-up and pull-down devices. Zardalidis & Karafyllidis [13] have introduced SECS, a tool taking into account the stochasticity of SETs by using Monte Carlo and the free energy of the circuit to estimate the rates of tunneling. A SPICE interface eases schematic capture. Sulieman and Beiu [14] have successfully compared different SET-based full adders, including not only delay and design complexity, but also sensitivity to variations. Their work was based on SIMON and Matlab. SIMON is the most well-known simulator for SET devices and circuits [15]. It simulates co-tunneling using Monte Carlo and master equation, and it has also been used in this paper.

IV. A LOW POWER/ENERGY COMMUNICATION SCHEME

Hexagonal and triangular arrays (inspired from [4], [6]) can be seen in Fig. 2. For the hexagonal array, the basic building block (equivalent to the functioning of a voltage-gated ion channel) could be an SET-based two-input OR (OR-2) gate, while for triangular array, we could use a three-input OR gate (OR-3). We designed and simulated both gates using SIMON [15]. OR-2 was built using NOR-2 followed by an INV (see Fig. 3) and the OR-3 using a NOR-3 and an INV. OR-2 and OR-3 gates map alternatively onto the nodes of the hex-connected arrays (Fig. 2). To mimic the transmission of an action potential (on an axon), we have used pulses (spikes) that are 1µsec wide (as the propagation delay of the OR-2 is about 0.5µs), at 10ms intervals (see Figs. 4, 5, 8, and 9). The input vector sequence for OR-2 is: 00, 11, 00, 10, 00, while for OR-3 the sequence is 000, 111, 000, 110, 000, 100. Fig. 4 shows the input pulses and the corresponding output for OR-2. Fig. 8 shows the inputs and output for OR-3.

We estimated power and energy as:

$$P_{\text{avg}} = \frac{V_{dd}}{T} \int_{t=0}^{T} i(t)dt \quad \text{and} \quad E = V_{dd} \int_{t=0}^{T} i(t)dt,$$

where the supply voltage is $V_{dd} = 6.5\text{mV}$, $i(t)$ is the instantaneous current, $P_{\text{avg}}$ is the average power, $E$ is the energy, and the total time $T$ is 40ms.

Fig. 6 shows the instantaneous P and PDP for an OR-2 gate which is used as a node of the hexagonal array. An axon is an array-based communication link (as in Fig. 2), where all the nodes are transmitting the same data (either “0” or “1”). Interestingly, the transition from “00” to “11” exhibits lower power and energy consumption than the “00” to “10” transition (see data in Table I). Similarly, Fig. 10 shows the P and PDP for an OR-3 gate, corresponding to a node of the triangular communication link presented in Fig. 2. We get higher P and PDP for “000” to “100” transition than the
other transitions like “000” to “111” and “000” to “110”. The maximum P and PDP for the OR-3 gate are nearly 6× higher than the ones for OR-2.

We can now estimate the energy required to propagate (communicate) information at a distance. For CMOS such information is available [19], so transmitting a 64-bit word over one millimeter is known to require about 25pJ. In order to estimate the energy required by our SET solutions, we consider the size of an SET transistor to be about 1nm (similar to a voltage-gated ion channel, but also consistent with requirements for room temperature operation [5]). An SET gate should occupy less than 100nm×100nm, while the distance between SET gates is considered 100nm. Therefore, the estimated number of SET gates covering a distance of 1nm is 1mm/100nm × 10,000 SET gates. Additionally, as suggested in [4][6] and implemented by axons and dendrites, we need several SET gates (ion channels) in parallel (contributing to enhancing reliability). It follows that structures like those presented in Fig. 2 would have several tens of thousand of ion channels (SET gates). We consider 100,000 SET gates per 1mm. So sending one bit of information over 1mm in current CMOS consumes 25pJ/64-b = 0.4pJ. From Table I, the energy per SET gate is between 1.013E-019 and 4.77E-019 J as all the gates are going to transmit the same information (either all 0s or all 1s). It follows that a 1mm SET-based communication would use at most 100,000×4.77E-19 = 0.047pJ. This leads us to the conclusion that the proposed axonal communication scheme could be at least 10× more energy efficient than current CMOS solutions.

CONCLUSIONS

In this paper, we have considered SET-based gates as building blocks for emulating ion channels. The investigation aimed to identify practical limits for ultra-low power/energy communications when using electronic principles. For a hex-shaped array, we found that our SET-based solution would offer better than 10× energy savings over current CMOS communications. We plan to continue investigating the power and the energy of other array-based structures (both for communication and for computations [4], [6]), looking into alternate SET implementations like those suggested in [16] and [17]. Additionally, the reliability of such arrays will have to be considered as affecting power/energy. Finally, we also plan to study the effect of temperature on the operation of our scheme, and also to compare such solutions with other approaches such as steep response devices.

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### Table I. OR-2 Power/Energy for the Different Transitions.

<table>
<thead>
<tr>
<th>Time interval [ms]</th>
<th>Input vector</th>
<th>Average Power [W]</th>
<th>Energy [J]</th>
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<tbody>
<tr>
<td>10 to 20</td>
<td>00</td>
<td>11</td>
<td>4.77E-017</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>11</td>
<td>4.77E-019</td>
</tr>
<tr>
<td>30 to 40</td>
<td>00</td>
<td>10</td>
<td>5.93E-016</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>10</td>
<td>5.93E-018</td>
</tr>
</tbody>
</table>

### Table II. OR-3 Power/Energy for the Different Transitions.

<table>
<thead>
<tr>
<th>Time interval [ms]</th>
<th>Input vector</th>
<th>Average Power [W]</th>
<th>Energy [J]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 to 20 ms</td>
<td>000</td>
<td>100</td>
<td>1.013E-019</td>
</tr>
<tr>
<td></td>
<td>110</td>
<td>11</td>
<td>2.245E-015</td>
</tr>
<tr>
<td>30 to 40 ms</td>
<td>000</td>
<td>110</td>
<td>2.245E-017</td>
</tr>
<tr>
<td>50 to 60 ms</td>
<td>000</td>
<td>100</td>
<td>3.882E-015</td>
</tr>
<tr>
<td></td>
<td>111</td>
<td>11</td>
<td>3.882E-017</td>
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</tbody>
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REFERENCES


