GLOBAL JOURNAL OF ENGINEERING SCIENCE AND RESEARCHES

QUANTUM DOT CELLULAR AUTOMATA

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ABSTRACT
Quantum-dot cellular Automata (QCA), a viable alternative to current CMOS, is gaining its prominence in digital circuit due to its very high device density and clocking speed. This paper reviews QCA and the different work done concerning to QCA. The different approach to computing with QCA by implementing QCA analogy to traditional logic devices will be discussed. Finally QCA computation and QCA clocks are discussed.

Keywords- *Quantum-dot cellular Automata (QCA), Boltzmann's constant, Resonant Tunneling Diodes (RTD's), Tunneling Phase Logic (TPL), Silicon on Insulator (SOI), Cellular Neural Networks (CNN), Single Electron Tunneling (SET), Tunneling Phase Logic (TPL), Lattice-based Integrated-signal Nano cellular Automata (LINA).*

1. INTRODUCTION
Today many integrated circuits are manufactured at 0.25-0.33 micron processes. As device sizes decrease to an order of 0.05 microns (a technology that is currently unrealizable), physical limitations of conventional electronics including power consumption, interconnect, and lithography will become increasingly difficult to surmount. In fact, studies indicate that as early as 2010, the physical limits of transistor sizing may be reached. Thus, it may not be possible to continue the norms of doubling the number of devices in a microprocessor every two years and doubling the clock rate every three years. Consequently to maintain trends of increasing microprocessor performance, other technologies should be studied. International Technology Roadmap for Semiconductors (ITRS) has proposed a few alternative technologies that can replace the transistor based computation in the near future. Some of them are, Resonant Tunneling Diodes (RTD's), Single Electron Tunneling (SET), Quantum Cellular Automata (QCA), Tunneling Phase Logic (TPL), Carbon Nano-Tubes (CNT) and Silicon on Insulator (SOI).

2. QCA
QCA seems to be the most promising technology that would replace CMOS devices in the near future. To replace CMOS at the nano scale, technology must overcome two important constraints: 1. With respect to contacts, 2. With respect to the interconnects. The first constraint, if a single-molecule device must be positioned between two or three macroscopic leads, the size of the leads would dominate the actual device size, losing the inherent advantage of single molecule size, if single molecules are to be connected directly to each other, then the challenge of "wiring up" vast number of molecular interconnects may also prove to be a futile exercise. First proposed in 1994 by Lent et al. , unlike conventional computers in which information is transferred from one place to another by means of electrical current, QCA transfers information by propagating a polarization state. QCA is based upon the encoding of binary information in the charge configuration within quantum dot cells. Computational power is provided by the Columbic interaction between QCA cells. No current flows between cells and no power or information is delivered to individual internal cells. The local interconnections between cells are provided by the physics of cell-to-cell interaction due to the rearrangement of electron positions. These cells are fabricated using quantum dots with freely moving electrons between them. Quantum dots can be formed either in hetero structures or Si/SiO2 two-dimensional electron gases (2DEGs). Quantum dot Cellular Automata offers a new transistor less computing paradigm in nanotechnology. It has the potential for attractive features such as faster speed, smaller size and low power consumption than transistor based technology. QCA exploits the interaction of electric and magnetic field polarizations for effective Boolean logic implementations. Hence QCA can be broadly classified into two types: Charge based and magnetic based. In charge-based QCA, the displacement of the electrons from one dot to the other affects the computation, while in magnetic QCA, magnetic dipole interactions effect the computations. In charge based QCA we refer to the alignment of electrons along one of the diagonal axes as its Polarization. QCA will correctly resolve to its ground state only if the relation $kT/\Delta)\ \ln(n) < 1$ holds, where k is Boltzmann's constant, is temperature, Δ is the energy difference between the ground state and the first excited state, and n is the number of cells in the automaton. For a given number of cells, a larger Δ translates into a higher operating temperature.

3. QCA BASED DESIGN
If In an effort to successfully develop a viable, understandable and usable QCA architecture, the following four tasks have been accomplished:

ISSN 2348 – 8034
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1) The first microprocessor data flow has been designed completely with QCA devices.
2) Floor planning techniques have been developed to efficiently design and layout QCA circuits to allow for the fastest possible clock rate and circuits with the minimum required area.
3) A library of design rules for QCA circuits has been built.
4) A simulator for QCA program has been written.

This allows a QCA design or architecture to be constructed and simulated in a easy and efficient manner

4. QCA GATES

Inverter

The QCA cells can be arranged in a particular fashion to easily create traditional logic gates. The basic gates in QCA technology are the majority gate and the inverter. Figure (a) & (b) shows two ways of creating inverters.

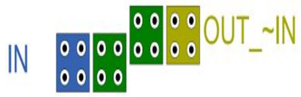

Fig. (a) Inverters (way-1)

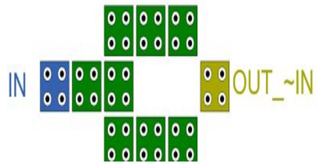

Fig (b) Inverters (way-II)

Majority, AND and OR Gate

The majority gate is illustrated in Figure (c). The output F is defined as F = B+AC+BC. The output cell of the gate polarizes to the computation cell in the center of the gate. The output F can be propagated using a QCA wire which can then act as an input to other gates. The majority gate can be used to build the AND and OR gates. If one of the inputs is fixed to 0/1, the resulting function F is the AND/OR of remaining two inputs. Figure (c) & (d) shows AND and OR gates.

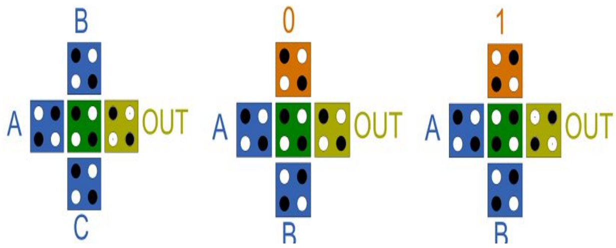

Fig.(c)Majority voter gate.Fig.(d)ANDgate.Fig.(e)OR gate

NAND Gate

A NAND function could be obtained by using an inverter in front of an AND gate as shown in figure (f).

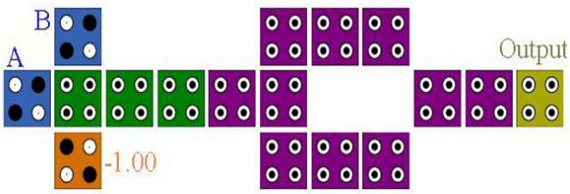

Fig. (f) NAND gate

5. COMPUTATION IN QCA

In QCA the computation is accomplished by the mapping of the many-body ground state to the state representing the problem solution as shown in Figure (g).

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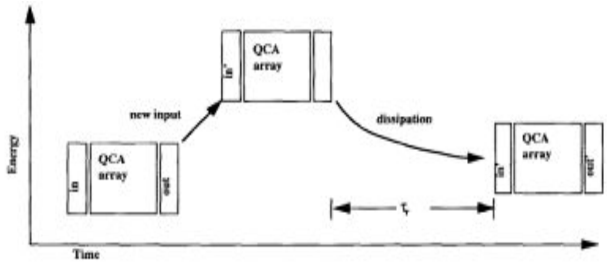

When the state of the input cell changes, the array enters into an excited state. The temporal evolution of the array from this point is quite complicated leading to quantum oscillations and reflections dissipating energy to the environment through the emission of phonons in the substrate, Plasmon in surrounding metallic gates etc depending on the specific details of the physical implementation of the dot structure. After the characteristic relaxation time T, the transient phase ends, the system dissipates its extra input energy and settles into its new ground state appropriate to the new boundary conditions supplied by the input cell. The output cells also would have settled into their new state, reading which reveals the solution to the computational problem. Hence the switching of a QCA cell can be classified in two ways

1. Abrupt Switching, where energy is dissipated and
2. Adiabatic Switching, where macroscopically no dissipation occurs.

6. QCA CLOCK

Unlike the standard CMOS clock, the QCA clock has more than a high and a low phase and it is multi-phased. Individual QCA cells are not timed separately. During the first clock phase, the switch phase, QCA cells begin unpolarized and their interdot potential barriers are low. The barriers are then raised during this phase and the QCA cells become polarized according to the state of their driver (i.e. their input cell). It is in this clock phase that the actual computation (or switching) occurs. By the end of this clock phase, barriers are high enough to suppress any electron tunneling and cell states are fixed. During the second clock phase, the hold phase, barriers are held high so the outputs of the subarray can be used as inputs to the next stage. In the third clock phase, the release phase, barriers are lowered and cells are allowed to relax to an unpolarized state. Finally, during the fourth clock phase, the relax phase, cell barriers remain lowered and cells remain in an unpolarized state. The four clock phases are illustrated in two different ways in figure (h) & figure (i).

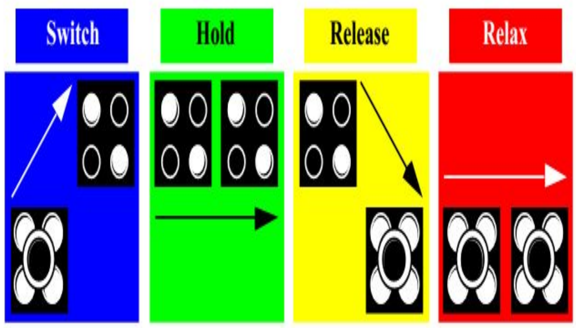

Fig. (h) The four phases of the QCA clock.

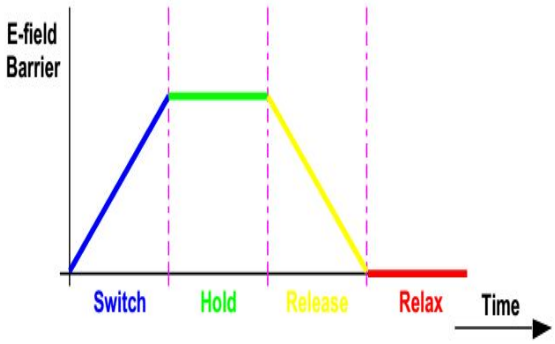

Fig. (i) The four phases of the QCA clock (an alternative expression)

7. LIMITATIONS OF QCA DEVICES

The QCA implementations studied so far are limited to very low temperature operation,E4 K or lower. For any reasonable number of cells, operating temperatures need to be below 1 K. If such low temperatures are necessary, it does not seem likely that QCA will find any practical use. Thus, a good deal of research has focused on increasing the operating temperature of QCA. One approach has been to re-engineer the standard cell while another has been to investigate molecular implementations.

8. QCA APPLICATIONS

A number of applications have been suggested for QCA. Pasky has suggested combining several gates into macrocells which can then be put together in regular arrays to provide useful behavior. These macrocells, laid out in 2-D, provide behavior analogous to the time evolution of a 1-D cellular automaton. He has specifically designed a 4-input macrocell which provides behavior that could be useful for finding the centroid of a one-dimensional array of signal inputs. Each macrocell consists of eight gates and receives inputs from four other cells. The macrocells are arranged in arrays and the inputs for a cell in one row come from the nearby cells in the previous rows. Toth and his co-workers have explored the possibility of using QCA to implement the cellular neural networks (CNN) first proposed by Chua. In a cellular neural network, individual processing elements are locally connected to neighboring units. Given outside input plus input from the neighborhood, the processing element produces its output. This output can be fed back into the element and its neighbors, if desired, and the system iterated until convergence is achieved. Toth has demonstrated a mapping between the characteristics of a CNN with the physics of QCA behavior. For example, the local connectivity of a cell in a CNN maps to the rapidly decreasing influence of more distant cells in a QCA. Finally, Toth describes an autonomous CNN whose synaptic law and state equation are based upon a quantum model of the cellular array. A linear CNN of this sort exhibits the same propagation as does a complete many-particle basis calculation of a QCA wire. Toth notes that the next step is expand the CNN into a second dimension. A related application of QCA is as highly parallel image processors. Fountain notes that an automaton is effectively a single instruction, multiple data (SIMD) device (CNN are also SIMD devices and have widespread application in image processing). Fountain describes a SIMD array with instruction pipelining and describes a QCA implementation of the system.

9. QCA RESEARCH

Some of the leading research groups currently involved in different areas of QCA research is;

- C. Lent et. al., J.Timler et.al of University of Notre Dame- Device and Fabrication level.
- D. Tougaw et.al of Valparasio, IN- Device and Logic level.
- M.Macucci et.al of University of Pisa-Device and Fabrication level.
- K.Walus et.al. Of University of Calgary- Logic level.
- P. Kogge et.al. and Niemier et.al of University of Notre Dame- Architecture and testing.
- F.Lombardi et.al. and Tahoori et.al of North Eastern University- Architecture and testing.
- K. Wang et.al.of University of California-Los Angeles-Architecture and testing.
- J. Abraham et.al.of University of Texas, Austin- Architecture and testing.
- A.Dzurak et.al. Of University of New South Wales-Fabrication level.
- D. Jamieson et.al. of University of Melbourne-Fabrication level.

10. FUTURE SCOPE

QCA provides the possibility of THz switching, molecular scaling, and provides particular applicability for advanced logical constructs such as reversible logic and systolic arrays within the paradigm. These attributes make QCA an exciting prospect; however, current fabrication technology does not exist which allows for the fabrication of reliable electronic QCA circuits which operate at room-temperature. Furthermore, a plausible path to fabrication of circuitry on the very large scale integration (VLSI) level with QCA does not currently exist. This has caused doubts to the viability of the paradigm and questions to its future as a suitable nanoelectronic replacement to CMOS. In order to resolve these issues, research was conducted into a new design which could utilize key attributes of QCA while also providing a means for near-term fabrication of reliable room-temperature circuits and a path forward for VLSI circuits. Forthcoming Lattice-based Integrated-signal Nano cellular Automata (LINA) designs are based on QCA and provide the same basic functionality as traditional QCA. LINA also retains the key attributes of THz switching, scalability to the molecular level and ability to utilize advanced logical constructs which are crucial to the QCA proposals. LINA designs provide significant improvements over traditional QCA in terms of fabrication, LINA's lattice-based structure allows precise relative placement through the use of self-assembly techniques seen in current nano particle research. LINA also allows for large enough wire and logic structures to enable use of widely available photo-lithographical patterning technologies. These aspects of the LINA designs, along with power, timing and clocking results, have been verified through the use of new and/or modified simulation tools specifically developed for this purpose.

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