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Quantum Dot Cellular Automata: A Review

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ABSTRACT –Shockley's transistor invented in 1952 has shrunk immensely as the years pass by, making the electronic computers very compact and one of the most powerful devices of the century. However advancements in Microelectronics as per Moore's law, face huge technical barriers in the future of transistor based computation due to the limitations posed at the nanoscale size. In view of this the International Technology Roadmap for Semiconductors (ITRS) has indicated several new technologies that are likely to replace the transistor based computation in the near future. Some of these include Resonant Tunneling Diodes (RTDs), Single Electron Tunneling (SET), Quantum Cellular Automata (QCA), and Tunneling Phase Logic (TPL). Among these, QCA seems to be the most promising emerging technology, as a viable alternative to CMOS. In this paper an effort has been made to present the review of the work carried out in QCA till date, from the time of its invention in 1940.

I INTRODUCTION

Limitations on the miniaturization of transistor based technology beyond the nanoscale have predicted its demise since 1970's [1]. Some of the barriers include off-state leakage currents, quantum effects, fabrication facilities, verification tools etc... As the dimensions of the device approach nanometer, physical effects exhibited transform from bulk properties to quantum effects. Hence intense research in progress mainly focuses on hetero structures with vertical nano dimensions for resonant tunneling and nanostructures with ultra small lateral dimensions such as quantum dots and quantum wires for ballistic electron motion, electron-wave interference, and single-electron tunneling [2].

In this view, the International Technology Roadmap for Semiconductors (ITRS) has proposed a few alternative technologies that can replace the transistor based computation in the near future [3]. Some of them are, Resonant Tunneling Diodes (RTD's), Single Electron Tunneling (SET), Quantum Cellular Automata (QCA), Tunneling Phase Logic (TPL), Carbon nano-tubes and Silicon on Insulator (SOI). Among these QCA seems to be the most promising technology that would replace CMOS devices in the near future.

At the nanometer scale, phenomenon of single electron tunneling becomes important as the device capacitance is so small that the electrostatic charging energy required to adding a single electron to the device exceeds the thermal energy [4]. Any approach that can replace CMOS at the nanoscale must overcome two important constraints: 1. With respect to contacts, 2. With respect to the interconnects. Elaborating the two, 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. And also 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. QCA solves these problems by coupling the molecules directly to other molecules [5], avoiding the cost of intervening leads except at the inputs and outputs of the entire array, and also it uses the Columbic coupling between the molecules [6] to provide robust operations without the need for precise control of current flow from molecule to molecule, thus eliminating the need of interconnects [7]. In QCA, quantum dots are used for digital computation [8], hence it provides outstanding energy efficiency [9], high density [10], and fast computing devices [11].

Theoretically the idea of cellular automata (CA) was introduced in early 1940s by Von Neumann and Ulam [12]. Next in 1960s Conway developed the Game of Life, which simulated CA by modeling the interaction of cells based on mathematical rules [13] and multiple valued cellular automata dynamics. In the year 1990, Kikukazu Sakurai et al. proposed the organic quantum computing system models based on quantum dot device architectures [4]. Later in the year 1993 Lent et al. experimentally demonstrated the possibility of Quantum Dot Cellular Automata cell, with Aluminum Island acting as Quantum dots [14].

A quantum dot is a region in the cell structure where charge can localize. A QCA cell consists of '2n' quantum dots with 'n' mobile electrons, which can tunnel between the quantum dots of a cell. The compensating positive charge is fixed and immobile [15]. Tunneling out of the cell is completely suppressed due to the potential barriers between the cells. Columbic repulsion between the electrons within a cell forces them to occupy dots which maximize their separation. Therefore, when the cell's dots are arranged in a square shape, the electrons tend to occupy diagonally opposite corners of the square [16].

Over the last few decades research work carried out on the electron transport in quantum dots has proved the fact that the resulting phenomena are evident only at very low temperatures [17]. Correct functioning of the QCA cells requires a very low operating temperature to distinguish the ground or lowest energy state from the first excited or next higher energy state. QCA will correctly resolve to its ground state only if the relation $(kT/\Delta)\ \ln(n) < 1$ holds, where k is Boltzmann's constant, T 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 [18].

Fabrication of Quantum dots is possible using both molecules and metal dots. However molecular QCA can be fabricated with a much higher degree of regularity and on a much smaller size scale than their metal-dot counterparts. Furthermore, molecular QCA can operate at room temperature [19]. Organization of the paper is as follows: Structure of QCA cell is introduced in the section II. Section III discusses the computational methodology. Section IV discusses the details of various structures implemented in QCA followed by the conclusions in section V.

II QCA CELL

In Quantum Dot Cellular Automata a quantum cell forms the basic element using which the structures are laid. 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). Two dimensional electron gas quantum dots in a cell can be made of Hydrogen, Helium or Lithium as shown in Fig.1a [20]. While in hetero structures, functioning QCA cell is demonstrated using 1.Ga As/AlGaAs [23]. 2. Indium deposition on a GaAs substrate [21]. 3. Al/AlO tunnel junctions [22].

Quantum dots can be fabricated with a variety of techniques [23]: 1.lateral surface gates producing fringing fields which further confine carriers in a two-dimensional electron gas, 2.Self assembled semiconductor dots, and 3.Chemically synthesized organic molecular structures [24]. Quantum dot atoms can be placed in close enough proximity to form quantum dot molecules as shown in Fig.1b [25]. A number of studies have been carried out to determine the feasibility of a technology based on interacting quantum dots in the long run [27-30].

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 [17]. In charge based QCA we refer to the alignment of electrons along one of the diagonal axes as its “Polarization”. The polarization of a cell in an arbitrary state can be defined from the expectation values of the charge on each dot [26-30]. Even a slight polarization in a neighboring cell induces complete polarization in the target cell. This means that at every stage or cell the signal level is restored. Thus the physics of the cell to cell interaction overcomes the imperfections in processing and irregularities in cell geometry, while transmitting the information.

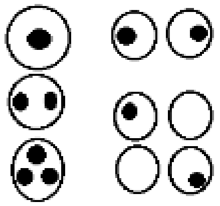

[a] [b]

Fig.1: Quantum Dots, [a] Atoms [b] Molecules

A few mixed-valence complexes have been investigated as possible molecular QCA candidates: 1. Trans RU (dppm)2 (CCFc) (NCCH2C H2NH2) dictation synthesized and attached on the surface of a Si substrate. 2.Oxidation of $\{\eta^5–C_5H_5\}Fe(\eta^5-C_5H_4)\}_4$ $(\eta^4–C_4)Co(\eta^5–C_5H_5)$ containing four ferrocene groups acting as four redox active centers giving rise to 2+ ion having 2-electron, 2-hole mixed-valence states [31]. 3. BIS-Ferrosene has been synthesized as a possible molecular QCA [32]. Two Ferrosenes represent the dots, a carbazole bridge provides the isolation between them and the thiol molecule allows the molecule to bind to the substrate. BIS-Ferrosene is the most promising candidate for molecular computation due to its bistable properties which allow the digital information encoding and it is sensitive to a particular electric field.

As cell size decreases, the energy separations between states increase and higher temperature operation is possible. A standard semiconductor cell having a quantum dot size of 10nm works up to about 7 K; at higher temperatures the cell–cell response function becomes nearly linear. For a macromolecular cell, if the near-neighbor distance is reduced to 2 nm with a relative dielectric constant of unity the operating temperature increases to 700K [18]. Investigations have proven that the size of the quantum dots must be in the order of 1–2 nm to facilitate room-temperature operation. This shows QCA cells must be created using single molecules [33]

.Various possible cell architectures have been studied for implementing the hardware using QCA: 1. 5 - Logically interacting Quantum Dot cell: It consists of four quantum dots on the corners of a square and one central dot. The cell is occupied by two electrons. Tunneling occurs between near neighbors and next-nearest neighbors but the barriers between cells are assumed sufficient to completely suppress electron tunneling between cells [34]. 2. 4 - logically interacting-Quantum Dot cell: It consists of two electrons and four logically interacting quantum dots, though this approach has been widely accepted, it may not be the most efficient and optimal choice [35] [36]. 3. 2-D QCA cell: It is a lattice structure, which uses clocked cells consisting of only two logically interacting quantum dots. Comparatively it improves the design and simulation reliability by reducing the total number of electrons and quantum dots in circuitry [37]. 4. Split current QCA cell (SCQCA): Cell proposed in [35] and [26] is still behind current fabrication capabilities. In SCQCA electron tunnelling occurs along the vertical direction, where highly controllable deposition techniques are able to deposit very thin films and effectively tune the device parameters. This concept lends itself to fabrication using currently available technologies [36]. 5. Six-dot QCA cell: It enables the clocking of QCA devices via an electric field generated by a layout of clocking wires [37]. Four dots connected by tunnel junctions, form the QCA cell, while the adjacent two dots can be used as detectors [38].

III COMPUTATION IN QCA

An array of interacting quantum cells can be considered as quantum-dot cellular automata [39]. No tunnelling should occur between cells, and the polarization of the cell should be determined only by Columbic interaction of its neighbouring cells. The expectation values pi of the charge on each dot define the polarization [40] of the cells according to the equation 1:

$$P \equiv \frac{(\rho 1+\rho 3)-(\rho 2+\rho 4)}{\rho 1+\rho 2+\rho 3+\rho 4} \quad ---------- \; 1$$

In classical computing P can take only two values +1 and -1. But in quantum computing due to superposed states, P can vary continuously between -1 and +1 as shown in Fig. 2 [41].The QCA paradigm is edge-driven, which means both energy and information flow in from the edges of the array only. It also means that power is only supplied at the edges of the device, and interior of QCA array needs no supply [42]. There are no direct contacts to the interior cells and there are no power rails. Thus interior cells cannot be maintained far away from their ground state.

In QCA the computation is accomplished by the mapping of the many-body ground state to the state representing the problem solution [23] as shown in Fig.3. 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 [20].

IV QCA STRUCTURES

The first step in implementing QCA structures is manufacturing a binary wire and demonstrating its logical behavior [43]. Linear arrays of cells interact coulombically with neighboring cells settling into one of the ground-state polarization due to bistable saturation, which can be used to transmit binary information along the line of cells [44]. In QCA, wires can be implemented in two different ways: 1. Binary wire implemented with the cells of 90 degree orientation. 2. Inverter chain implemented with the cells of 45 degree orientation. Corners require turnings in any design. Two types of corner turns were investigated [45]: 1. Lent corner: Just passes the signal as it is. 2. Tonomata corner: Inverts the signal as shown in Fig. 4a and 4b.Two types of inverters were investigated [46]: 1. Tougaw and Lent inverter: Normal inverter, 2. Lusth and Jackson inverter : A minimal cell inverter as shown in Fig. 5a and 5b.All these structures are asynchronous. Here the only source of energy is the applied input; hence neither power gain nor control over the electron switching is possible. To overcome these obstacles clocked QCA was proposed [47][48] and experimentally verified [49][50]. The clocking phenomena is used to alter the tunnel barrier height between intracellular QDs to either freeze cells in their logic state- a so-called hold phase, or reduce electron localization in the dots to produce a state that has no net effect on the surrounding cells- a so-called null phase. Clocking can be classified into two types:

1. Keyes and Landauer clocking [51]: It consists of a particle or an electron in a potential well that can be varied between a monostable and a bistable state by applying an external signal. 2. Adiabatic clocking [52]: An extra dot added between the top and bottom dots, acts as a potential barrier which can be modulated using a clock signal.

Crossover in QCA is implemented in two different ways:
1. Coplanar wire crossing: cells with 90 degree and 45 degree orientation are used in a single plane. 2. Multiplanar wire crossing : Cells with 90degree orientation are used in multiple planes. Manufacturing nano-scale cells with two different orientations is the most challenging task [53]. Furthermore, excessive wire-crossing structures may affect the function of the circuit [54].

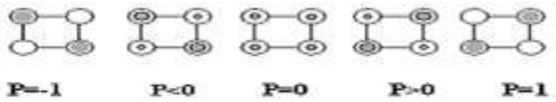


Fig.2: Polarization of 4- Quantum Dot cell

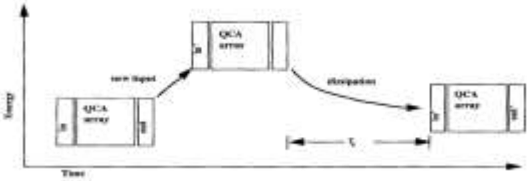


Fig.3: Edge driven computation in QCA

A. BASIC GATES

In the early phase of implementing circuits using QCA, a majority voter [MV] or a majority gate [MG] shown in Fig.6 was the most widely accepted basic gate, using which other logic could be implemented [55]. The AND and OR gates can be realized using a majority gate by fixing one of its input to '0' and '1' respectively. But the major drawback is that the majority gate does not form the complete logical set. It is not an universal gate as it cannot realize the logical NOT operation. Hence the functionally complete set is a MV along with the NOT gate [MV, NOT].

Fig. 4a. Lent corner,

4b. Tonomata Corner.

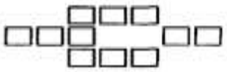
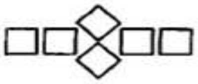


Fig. 5a. Lent inverter,



5b. Lusth inverter

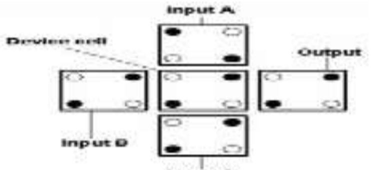


Fig. 6: Majority Voter or Majority Gate

To overcome this drawback an And-Or-Inverter (AOI) gate [56] with embedded AND, OR and INV functions was proposed. Though it provides the universal functionality, it suffers from the limitation of proper separation of input and output binary wires. It also requires more space and is more complex. Next a Nand Nor Inverter (NNI) universal gate was proposed [57] as a majority voter with two inverted inputs that could realize all the logic functions. It is very effective and also ensures very less space compared to all other gates. Two new gates AND-NAND and OR-NOR [58] were proposed for implementing QCA circuits with minimum garbage outputs, and minimum area. In order to reduce the number of wire crossings, universal logic gate (ULG) [59] was proposed. Compared to the Majority-Inverter based design, the ULG based implementation achieves 22.2% reduction in terms of the number of wire-crossings.

B.ADDER

First adder was implemented using standard QCA cells having four quantum dots with an inter dot distance of 20nm and a relative dielectric constant of 10 [20], followed by full adder circuit designed with QCA cells having quantum dots of size 10 nm occupying an area of about 1 square micron [29]. These full adder circuits were realized using 5 three input majority logic gates and three inverters [52]. Later Ripple Carry Adder [RCA], Carry Look Ahead adder [CLA] and Carry save adder [CSA] are designed using Pipelining technique with no feedback [60]. As RCA is the simplest adder, its complexity is less, but the input/output synchronization requires a larger area. Though the complexity of CLA is higher, its delay is lesser. CSA shows the highest complexity and largest area. One-digit decimal adders designed using three or five one-bit QCA full adders occupying a total area of 2.28 $\mu m^{2,}$ offering a overall delay of 8 clock cycles [61]. In view of cost efficient design, decimal adders namely Carry Flow Adder [CFA]-and Carry Look ahead adder are implemented [62]. CFA based BCD adder is the smallest QCA BCD adder, as it achieves a fastest speed than all previous designs with a latency of 4.75 clock cycles. It also achieves a lower overall cost with a reduction of more than 80% when compared to the present decimal adder.

C.MULTIPLIER

Initially multipliers were proposed using majority voters as the basic element. But these structures were not the optimized QCA structures [62][63]. Later Carry shift multiplier (CSM) and a carry delay multiplier (CDM) [64] architectures proposed based on FIR filter equations to minimize the latency of the output and delay of the carry. Wallace [65] and Dadda [66] tree multipliers are also implemented in QCA using majority voters.

D.DIVIDER

A restoring array divider composed of controlled full subtractor cells consisting of one full subtractor and one two input multiplexer are studied [67]. Due to restoring algorithm design is large and slow. However the performance can be improved using pipelined parallel structures.

E. SHIFT REGISTER

A two cell shift register is proposed in [68]. It operates at a temperature of 70mk. It is constructed using two capacitively coupled QCA latches L1 and L2. An interesting feature of this design is that the propagation of the information can be reversed by changing the clocking sequence and input gates. Hence this QCA shift register is a logically reversible device. The authors have further enhanced the gain of the shift register by the use of adiabatic switching through a clock [69].

F.MEMORY

Memory is of three types 1. Serial 2. Parallel 3. Hybrid. Serial-type memories are small in size but give higher latency in read and write operations. Larger the memory, slower is the response time [70]. The parallel-type on the other hand, have a stable latency, but the size is two or three times larger than the serial-type with the same number of data bits [71]. Hybrid memory is a trade-off between these two types. They have their size comparable to the serial-type, but their read speed is equal to the parallel-type [72]. A 4-bit memory layout proposed in [74], occupy's an area of 11.34μm^2. It takes 4 clock cycles for data to be stored in a register, and 5 clock cycles for data to be available at the output. A novel architecture for 16 bit RAM is proposed and simulated [75]. It consumes an area of 2.91μm^2 with a maximum read and write latency of 9 clock cycles.

G.ALU

The 4-bit arithmetic and logic unit proposed in [76] uses majority voter as its basic element and implements 10 different operations. It consumes a total of 14.27μm^2. A 4-bit Arithmetic and Logical Function Generator is implemented to accommodate 16 arithmetic and logical operations. It consumes a total area of 11.37 μm^2 with aid of 9 clocks to give the final output.

H.TESTING

Testing of QCA based designs has been investigated and has shown that only two test vectors on a QCA-based implementation can detect all stuck-at- faults with respect to the fault list on the original design [77]. A design-for-test scheme is presented based on a change in the structure of the design, in which the design is partitioned into a block of inverters and a block of majority voters resulting in a reduced test generation effort and test length.

V CONCLUSIONS

In this paper, a survey of various works carried out in the field of QCA with respect to (1).Materials used in fabricating the quantum dots, (2).Various QCA cell configurations, (3).Clocking mechanism, (4).Basic gate structure, (5).Adder, (6).Multiplier, (7).Divider, (8).ALU & (9).Testing is presented as a first step towards research on QCA and its applications.

REFERENCES

[1] Rairigh. D, “Limits of CMOS technology scaling and technologies beyond CMOS”, http: // www .drlock .com / papers / cmos _ survey. pdf. 2005.

[2] Craig. S. Lent, P. Douglas Tougaw, and Wolfgang Porod, “Quantum Cellular Automata: The Physics of Computing with Arrays of Quantum Dot Molecules”, Proceedings of IEEE workshop on Physics and Computation, 1994.

[3] International Technology Roadmap for Semiconductors (ITRS), http://www.itrs.net, 2007.

[4] Geboren te Tilburg, “Coulomb-Blockade Oscillations in Quantum Dots and Wires” Phillips Research Program, 5th Nov, 1992.

[5] C. S. Lent, P. D. Tougaw, W. Porod, and G. H. Bernstein, Nanotechnology 4, p. 49, 1993.

[6] C. S. Lent and P. D. Tougaw, Proceedings of the IEEE 85, p. 541, 1997.

[7] Enrique P. Blair and Craig S. Lent," Quantum-Dot Cellular Automata: An Architecture for Molecular Computing" IEEE conference on Nano Electronics, pp 14-18,2003.

[8] G.L. Snider, A.O. Orlov, I. Amlani, G.H. Bernstein, C.S. Lent, J.L. Merz, and W. Porod,”Quantum Dot Cellular Automata”, Nanotechnology, 4, 49, 1993.

[9] Ma, X., Huang, J. and Lombardi, F., “A Model for Computing and Energy Dissipation of Molecular QCA Devices and Circuits”, ACM J.Emerging Technologies in Computing Systems, vol.3, no.4, article 18, 2008.

[10] DeHon, A. and Wilson, M.J., “Nanowire-Based Sub lithographic Programmable Logic Arrays”, Proc. Int’l Symp. Field-Programmable Gate Arrays, pp.123-132, 2004.

[11] Seminario, J.M. et al., “A Molecular Device Operating at Terahertz Frequencies: Theoretical Simulations”, IEEE Trans. Nanotechnology, vol.3, no.1, pp.215-218, 2004.

[12] J. von Neumann, Theory of Self-Reproducing Automata, A. W. Burks, Ed. Urbana, IL: Univ. Illinois Press, 1966.

[13] M. Gardner, “Mathematical games: The fantastic combinations of John Conway’s new solitaire game of ‘life’,” Sci. Amer., vol. 223, pp. 120–123, Oct. 1970.

[14] C. S. Lent, P. D. Tougaw, W. Porod, and G. Bernstein,"Quantum Dot Cellular Automata”, Nanotechnology,4,49 1993.

[15] C. S. Lent and P. D. Tougaw, J. Appl. Phys. 74,4077, 1993.

[16] Enrique P. Blair and Craig S. Lent," Quantum-Dot Cellular Automata: An Architecture for Molecular Computing" IEEE conference on NanoElectronics,pp 14-18, 2003.

[17] Gary H. Bernstein" Quantum-dot Cellular Automata: Computing by Field Polarization" DAC, June 2-6, 2003, Anaheim, CA, USA.

[18] C. S. Lent and P. D. Tougaw, “A Device Architecture for Computing with Quantum Dots”, Proceedings of the IEEE, vol. 85 (4), pp. 541 -557, April 1997.

[19] C. S. Lent, Science 288, p. 1597, 2000.

[20] Sergei Studenikin' Louis Gaudreau" 2 Andy Sachraj:da' Piotr Zawadzki', Alicia Kam Jean Lapointe' Marek Korkusiuiskil and Pawel Hawrylak" Charging characteristics of a few electron triple lateral quantum of system in GaAs/AlGaAs.

[21] T. A. Fulton and G. H. Dolan, “Observation of single-electron charging effects in small tunnel junctions,” Phys. Rev. Lett., vol. 59, pp. 109–112, 1987.

[22] L.J. Geerligs, C.J.P.M. Harmans, and L.P. Kouwenhoven, Special issue of Physica B "The Physics of Few-Electron Nanostructures", Physica B 189,1993.

[23] M. Kemerink and L.W. Molenkamp, App. Phys. Lett. 65,1012 ,1994.

[24] P. D. Tougaw, C. S. Lent, and W. Porod, J. Appl. Phys. 74, 3558 (1993).

[25] C. S. Lent, P. D. Tougaw, W. Porod, and G. Bernstein,"Quantum Dot Cellular Automata”, Nanotechnology,4,49 (1993).

[26] P. D. Tougaw, C. S. Lent, and W. Porod, J. Appl. Phys. 74, 3558 (1993).

[27] C. S. Lent and P. D. Tougaw, J. Appl. Phys. 74,6227 (1993).

[28] P. D. Tougaw, C. S. Lent, J. Appl. Phys. 75, 1818 (1994).

[29] C. S. Lent and P. D. Tougaw, J. Appl. Phys. 74,4077 (1993).

[30] Jiao, J.; Long, G. J.; Grandjean, F. G.; Beatty, A.M.;Fehlner,T.P. J.Am.Cbem.Soc. J.Am .Cbem. Soc. 2003,125,15250.2003,125,7522.

[31] Azzura Pulimeno et al., “ Molecule Interaction for QCA Computation” 12th IEEE International Conference on Nanotechnology, 20-23 August, 2012.

[32] C. S. Lent, B. Isaksen, and M. Lieberman, “Molecular quantum-dot cellular automata,” J. Amer. Chem. Soc., vol. 125, pp. 1056–1063, 2003.

[33] Craig S. Lent and P. Douglas Tougaw, “Lines of interacting quantum-dot cells: A binary wire”, J. Appl. Phys. 74 (IO), 15 November 1993.

[34] C. S. Lent, P. D. Tougaw,W. Porod, andG.H Bernstein, “Quantum cellular automata,” Nanotechnology, vol. 4, pp. 49–57, Jan. 1993.

[35] I. Amlani, A. O. Orlov, G. Toth, G. H. Bernstein, C.S. Lent, and G.L. Snider, “Digital logic gate using quantum-dot cellular automata,”Science, vol. 284, pp. 289–291, Apr. 1999.

[36] Loyd r. Hook, iv and Samuel c. Lee," Design and simulation of 2-d 2-dot quantum-dot cellular automata logic, ieee transactions on nanotechnology, vol. 10, no. 5, september 2011 ,pp 996-1004.

[37] Konrad walus,r. Arief budiman, graham a. Jullien," Split current quantum-dot cellular automata—modeling and simulation" ieee transactions on nanotechnology, vol. 3, no. 2, june 2004.

[38] Enrique P. Blair and Craig S. Lent," Quantum-Dot Cellular Automata: An Architecture for Molecular Computing"IEEE conference on Nano Electronics, 2003, pp 14-18.

[39] Gary H. Bernstein, Greg Bazan, Minhan Chen,“Practical issues in realization of Quantum dot cellular automata”, Superlattices and Microstructures, Vol. 20, No. 4, 1996.

[40] G. Tóth and C. S. Lent, “Quasiadiabatic switching for metal-island quantum-dot cellular automata,” J. Appl. Phys., vol. 85, no. 5, pp.2977–2984, 1999.

[41] W. Porod, “Quantum dot devices and quantum-dot cellular automata,” in Visions of Nonlinear Science in the 21st Century, ser. A, J. L. Huertas, W.-K. Chen, and R. N. Madan, Eds., 1999, vol. 26, World Scientific Series on Nonlinear Science, pp. 495–527.

[42] G.Pavan et al.,“Implementation of Look Up Tables using Quantum Dots”, IEEE International conference on Advances in Engineering ,Science and Management-ICAESM, pp 275-278, March 30-31,2012.

[43] P. Douglas Tougaw and Craig S. Lent, ”Dynamic Behavior of Quantum Cellular Automata”, J. Appl. Phys. 80 (8), 15 October 1996.

[44] 0. Orlov, I. Amlani, G. Toth, C. S. Lent, G. H. Bernstein, and G. L. Snider, “Experimental demonstration of a binary wire for quantum-dot cellular automata”, Applied Physics Letters, vol. 74, 2875, 1999.

[45] T. Tanamoto, R. Katoh, and Y. Naruse, “A Novel Quantum Cellular Automata Logic with Loop Structures”, Japanese Journal of Applied Physics, vol. 33, part 2, no. IOB, October, 1994.

[46] J. C. Lusth and J. Jackson, “A graph theoretic approach to quantum cellular design and analysis”, Journal of Applied Physics, vol. 79, no. 4, February 1996.

[47] C. S. Lent and P. D. Tougaw, Proceedings of the IEEE. 85, 541 (1997).

[48] G. Toth, C. S. Lent, J.Appl.Phys. 85, 2977 (1999).

[49] C. S. Lent and P. D. Tougaw, “A device architecture for computing with quantum dots,” Proc. IEEE, vol. 85, no. 4, pp. 541–557, Apr. 1997.

[50] A. O. Orlov, I. Amlani, R. K. Kummamuru, R. Ramasubramaniam, G. Toth, C.S. Lent, G. H. Bernstein, and G. L. Snider, “Experimental demonstration of clocked single-electron switching in quantum-dot cellular automata,” Appl. Phys. Lett., vol. 77, pp. 295–297, Jul. 2000.

[51] R. W. Keyes and R. Landauer, “Minimal energy dissipation in logic,”IBM J. Res. Develop., vol. 14, pp. 152–157, 1970.

[52] C. S. Lent and P. D. Tougaw, “A device architecture for computing with quantum dots,” Proc. IEEE, vol. 85, pp. 541–557, 1997.

[53] D. A. Antonelli, D. Z. Chen, T. J. Dysart, X. S. Hu, A. B. Kahng, P. M. Kogge et al. “Quantum-dot cellular automata (QCA) circuit partitioning: Problem modeling and solutions,” Proceedings of the 41st ACM/IEEE Design Automata Conference (DAC-04), San Diego, CA, June, pp. 363- 368, 2004.

[54] K. Kim, K. Wu, R. Karri, “Quantum-dot cellular automata design guideline,” IEICE Transactions on Fundamentals of Electronics, Communications and Computer Sciences, E 89-A(6), pp. 1607-16, 2006.

[55] Rumi Zhang, Konrad Walus, Wei Wang, and Graham A. Julli, " A Majority Reduction Technique for Adder Structures in Quantum-dot Cellular Automata”, IEEE Trans on Nanotechnology, vol. 3, no. 4, Dec 2004, pp. 443-450.

[56] M. Momenzadeh, M. B. Tahoori, J. Huang and F. Lombardi, “Characterization, Test and Logic Synthesis of AND-OR-INVERTER (AOI) Gate Design for QCA Implementation”, IEEE Trans on Computer Aided Design of Integrated Circuits and Systems, vol. 24, no. 12, December, 2005, pp. 1881-1893.

[57] P. K. Bhattacharjee, “Efficient Synthesis of Symmetric Functions”, World Congress in Computer Science, Computer Engineering and Applied Computing (WORLDCOMP-2008) in International Conference on Computer Design (CDES’08), las Vegas, USA, July 2008, pp. 23-29.

[58] Pijush Kanti Bhattacharjee, "Digital Combinational Circuits Design By QCA Gates", International Journal of Computer and Electrical Engineering, Vol. 2, No. 1, February, 2010 1793-8163.

[59] Yinshui Xia, Keming Qiu," Design and Application of Universal Logic Gate based on Quantum-Dot Cellular Automata" 11th International conference on Communication Technology Proceedings, 2008,pp 335-338.

[60] Heumpil Cho, and Earl E. Swartzlander,"Adder Designs and Analyses for Quantum-Dot Cellular Automata", IEEE TRANSACTIONS ON NANO TECHNOLOGY, VOL. 6, NO. 3,pp 374-383, MAY 2007.

[61] Kharbash,and G. M. Chaudhry," The Design of Quantum-Dot CellularAutomata Decimal Adder", Proceedings ofthe 12th IEEE International Multitopic Conference, December 23-24,2008.

[62] Weiqiang Liu, Liang Lu and M´aire O’Neill,“Cost-efficient decimal adder design in quantum-dot cellular automata”, IEEE Transactions, 2012.

[63] K. Walus, G. A. Jullien, V. S. Dimitrov, “Computer arithmetic structures for quantum cellular automata”,. Conference Record of the Thirty Seventh Asilomar Conference on Signals, Systems and Computers, vol. 2, pp. 1435-1439, 2003.

[64] K. Walus and G. A. Jullien, .Design tools for an emerging SoC technology: quantum-dot cellular automata,. Proceedings of the IEEE, vol. 94, no. 6, pp. 1225-1244, 2006.

[65] Heumpil Cho, Earl E. Swartzlander, Jr.," Serial Parallel Multiplier Design in Quantum-dot Cellular Automata, 18th IEEE Symposium on Computer Arithmetic (ARITH'07), 2007.

[66] C. Wallace, “A suggestion for a fast multiplier,” IEEE Transactions on Electronic Computers, vol. EC-13, pp. 14–17, 1964.

[67] L. Dadda, “Some schemes for parallel multipliers,” Alta Frequenza, vol. 34, no. 1, pp. 349–356, 1965.

[68] Seong-Wan Kim, et.al.," Restoring Divider Design for Quantum-Dot Cellular Automata",2011 11th IEEE International Conference on Nanotechnology Portland Marriott August 15-18, 2011, Portland, Oregon, USA.

[69] Ravi Kummamuru, et.al, “A Quantum-dot cellular Automata Shift Register”,ieee Transactions, 2001.

[70] Craig S. Lent et.al.. **“**Power Gain in a Quantum-dot Cellular Automata (QCA) Shift Register”, IEEE transactions on quantum Dots and Devices, Nano 2001.

[71] D. Berzon and T. Fountain. A memory design in QCAs using the squares formalism. Proceedings Ninth Great Lakes Symposiam on VLSI 168-172, 1999.

[72] K. Walus,et.al..” RAM design using quantum-dot cellular automata. Technical Proceedings of the 2003,Nanotechnology Conference and Trade Show, 160-163, 2003.

[73] Kanjanawit Yanggratoke and Songphol Kanjanachuchai," Hybrid Quantum Cellular Automata Memory", Proceedings of ECTI-CON,pp 857-860, 2008.

[74] K. Walus,et.al. "Simple 4-Bit Processor Based On Quantum-Dot Cellular Automata (QCA)",Proceedings of the16th IEEE International Conference on Application-Specific Systems, Architecture and Processors (ASAP’05), pp 1- 6, 2005.

[75] Moein Kianpour, Reza Sabbaghi-Nadooshan “A Novel Design And Simulation of 16 Bits RAM Implementation In Quantum-dot Cellular Automata (QCA)”, IEEE Transactions, 2012.

[76] Vishnu C. Teja, Satish Polisetti, Santhosh Kasavajjala "QCA based multiplexing of 16 Arithmetic & Logical Subsystems-A paradigm for Nano Computing" Proceedings of the 3rd IEEE Int. Conf. on Nano/Micro Engineered and Molecular Systems January 6-9, 2008, Sanya, China.

[77] Mehdi Baradaran Tahoori and Fabrizio Lombardi, “Testing of Quantum Dot Cellular Automata Based Designs”, Proceedings of the Design, Automation and Test in Europe Conference and Exhibition (DATE’04),2004