Quantum Dot Cellular Automata: A Novel Circuit Design Approach

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Abstract: As an alternative to CMOS technology, researchers have proposed new technologies like FINFET, CNTFET, MTJ to improve the performance of the system. This paper presents some emerging technologies over CMOS-VLSI. Also the new polarization based digital logic design with quantum dots called Quantum dot Cellular Automata i.e. QCA is described here. In this new computing paradigm QCA cell is the fundamental unit to design logic structure in quantum domain. This technology achieves an effective design of logic circuits using QCA. In this paper basic QCA structures are designed with minimum number of QCA cells and with minimum complexity. So these structures can be used to design and simulate complex circuits in digital system. The simulation of the present work is done by QCA designer tool which facilitate rapid and accurate simulation.

Keywords: QCA, FINFET, CNTFET, QCADesigner tool, majority gate.

Introduction

The conventional transistor-based CMOS technology has followed Moore's Law, the transistors count is increased every 18 months which affects technology scaling [1]. As increase in technology scaling, many parameters like feature size, power, speed has to change. To enable more devices fabricated within a given area on a single silicon chip, the feature size have to be reduced. Also the other parameter such as power dissipation and line voltage reduces with increase in frequency performance [7].

There are some limitations of the individual devices when scaling down to sub-micron level. As technologies continued to scaling down beyond this level, it became impossible to reach the proper scaling of various device parameters [6].It is found that when modify one parameter such as performance causes unwanted variations in other areas like power. This results in power dissipation, non deterministic behavior of small currents like sub-threshold leakage current due to quantum tunneling[9]. It was therefore necessary to adapt new advanced options like a change in transistor structure. QCA is the new advanced nano technology alternative to conventional one. In this device logic states does not stored in voltage levels, but simply based on the position of individual electrons [2].The theory used by QCA is quantum theory or mechanics which explains the nature and behavior of the particle at atomic level like energy or light. QCA cell is the basic unit of QCA technology. Each cell has four quantum dots. Two electrons remain in a cell. Due to the columbic forces these electrons always try to repel from each other at the diagonal places in the cell. This leads to two polarization state, logic 0 and logic 1[3].This polarization based paradigm is used to implement some logic functions. These structures are designed using three different types of gates in QCA. These are Majority gate, INVERTER, Reversible logic gate. The Majority gate is used mostly to design the functionality due to its simplicity [2]. Then the proper arrangement of majority gate implements the structures of different combinations using cell minimization techniques and then simulated by QCA Designer tool that is QCAD tool.

This paper presents a recent emerging technology alternative with the MOSFET device in the nanometer regime. Also introduction to the operation of quantum-dot cellular automata (QCA) is reported.

Emerging Technologies

In digital electronics the researchers are mainly focused on increasing speed, and reduce the power consumption of the device. To overcome the challenges of conventional CMOS, new emerging technology needs to be introduced which may consist of advanced features and to replace the drawbacks of conventional technology[8][10].

1) FINFET Technology: FinFET technology is a promising technology used in future for design of integrated circuit[10].This technology provides higher scalability which is the need of today's electronic system[8]. The device FinFET is used to determine any fin-based structure. This is the device which improves electrical control over the channel conduction[6][10].However it reduces the short channel effect caused by leakage current. FINFET device delivers much improved short channel control through its fully depleted operation. Thus improving the device performance.

2) CNTFET Technology: To overcome the difficulties occurred during MOSFET scaling CNTFET is explored.It has most of the desired features to perform today's functionality [7].CNTFET (Carbon nanotube field effect transistor) uses the material for semiconducting channels is CNT (carbon nano tubes). Under high electric field or temperature gradients, Carbon nanotubes shows reliability issues [8].Due to different heat dissipation mechanisms, the self-heating effect is less in a semiconducting CNTFET. A small fraction of the heat generated during operating condition in the CNTFET is dissipated through the channel [9].
3) QCA Technology: A new technology based on QCA cells offers advanced computation to design functionality at nano meter range and to exploit the quantum effects when deals with small size. This technology might improve the conventional design technology(CMOS).The QCA has more advanced feature that it has high packing density because of the small size of the dots.In this new paradigm, the basic logic element is not a current switch, but depends on a small array of quantum dots, and the logic state is determined by the position of individual electrons within a quantum dot cell.

QCA Technology

Importance of Quantum Dots

Recent QCA technology uses quantum dot in a cell to perform the computation. The stable shape of islands of quantum dot has recently been explored for the cellular technology [2].Quantum dots (QD) are very small semiconductor particle. It has the size only in several nanometers that seems to be very small that their optical and electronic properties differ from those of larger particles. Their opto-electronic properties change as a function of both size and shape. It has the ability to trapped electrons in three dimensions. These are constructed by generating an island of conductive material covered by some insulating material [1].

Construction Of QCA

The main component of QCA is QCA cell which is constructed by quadratic cells.This is square shaped cell in which exactly four potential wells are located. The are located in each corner of the QCA cell[1]. In this,exactly two electrons are placed diagonally in the potential wells.The potential wells are connected by the electron tunnel junctions. This can be opened under a particular condition to travel the electrons through these tunnel junctions, by a clock signal [2]. If there is no any interaction from outside, due to the Coulomb force the two electrons in the QCA cell will try to repel from each other as far as possible. Hence they will occupy the exactly diagonally located potential wells. Because the diagonal is the maximum possible distance for them as shown in figure 1.

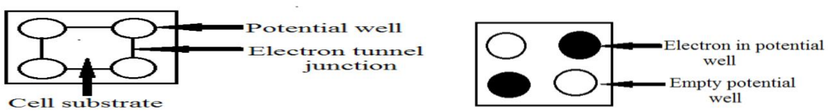


Fig. 1. Structure Of QCA Cell

Metallic Tunnel Junction in QCA

QCA cell consist of four quantum dot two of which are filled with electrons.These electrons placed at maximum position due to repulsion force. The electron tunnel junction is lay down in between these quantum dots which controls the transition of these electrons. Quantum tunneling refers in QCA to tunnel the quantum dots from one state to another based on tunneling theory. The tunneling theory explains that tunneling of electrons through barrier in QCA cell can be done only in the range of 1-3nm.If it exceeds this range then tunneling is not possible.Figure shows the QCA cell with magnetic tunnel junction.

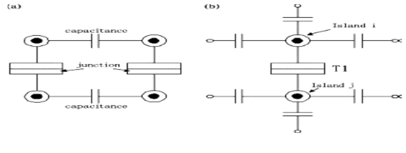


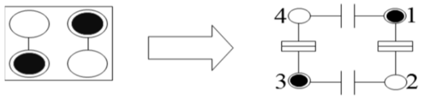
Fig. 2. QCA Cell with Magnetic tunnel junction

Quantum Dots operate as Cellular Automata

QCA is an promising emerging technology that takes advantage of quantum dots, which pretends at the scale of a few nanometers[3].Repelling force of electrons moves the charge to opposite corners of the quantum cell.Figure 3 shows the cells with quantum dot numbered as i=1,2,3,4.Polarization of QCA cell can be calculated by using following equation 2.4.1.

$$\frac{(P1 + P3) - (P2 + P4)}{(P1 + P2 + P3 + P4)} \quad ...... 2.4.1$$

Consider 1 if electron is present in quantum dot else 0.This results in two possible arrangements, representing binary 0 and 1.



Logic Gate Design

In this section some QCA structures are described.These circuits are designed with minimum number of cells by using cell minimization techniques. The techniques are 1)two cells inverter and 2) Majority Gate. Hence the proposed designs can be used to minimize the area as well as complexity[4].In QCA, the output is equal to majority neighboring states. The polarization of the central cell is then propagated as the output.Thus,majority gates and inverters are used to implement all combinational logic functions.

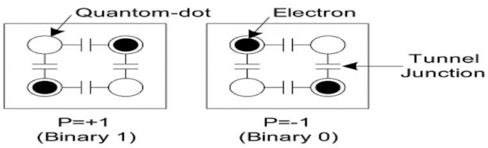


Fig. 3. Binary Representation Of QCA

A. Majority Gate

The majority gate is the fundamental logic gate in QCA.To design a single majority gate five QCA cells are necessary[2].Single majority gate performs three input AND,OR operation using the following equation.

$$AB + BC + AC \quad ...... 4.1.1$$

In this case A and B are the inputs and C is the control line or program line.

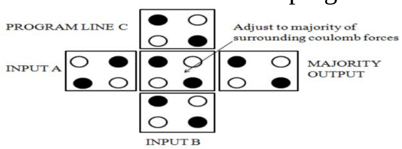


Fig. 4. Majority Gate

QCA NOT Gate

QCA NOT gate is constructed by simply placing the two QCA cells diagonally and this will produces the output binary 1 when the input is binary 0 and vice versa.

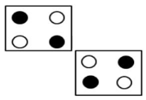
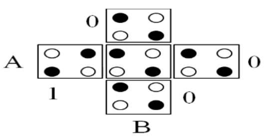


Fig. 5. QCA NOT Gate

QCA AND gate

The AND gate can be constructed by making all inputs of majority gate are 1 and thus the output becomes 1, otherwise 0.The function of AND effectively finds the minimum between two binary digits, just as the OR function finds the maximum between two binary digits[5].



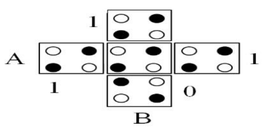


Fig. 6. QCA AND Gate

Fig. 7. QCA OR Gate

QCA OR Gate

It is a digital logic gate that finds the maximum between two binary digits, just as the complementary AND functions finds the minimum. To create an OR gate, control line input of majority gate must be zero[5].
Hence a majority gate has advantage that it has ability to perform certain arithmetic functions with just one majority gate. Hence the majority gate is used in QCA to design combinational circuits[4][5][6].The combination of majority gate and QCA inverter can be used to design and simulate logic gates like XOR,NOR,NAND.

QCA Implemetation

In this section, different logic gates are designed using single majority gate and simulated using QCA designer tool.QCADesigner is one of the designer tool which performs accurate simulation in quantum-dot cellular automata (QCA).This is the tool which is used for design computation in QCA[11].

An INVERTER

The basic concept behind the QCA inverter is that it simply inverts the input value.Mostly it is constructed by two QCA cells or nine QCA cells. This inversion in QCA performs proper simulation in many circuits[1]. The input polarization has two stable states binary 1 or 0.Hence two QCA cell corners connect diagonally and produces the opposite polarization at output[2]. One another way to design a QCA NOT gate using nine QCA cells which is more accurate. Here in this design one single QCA wire is divided into two separate wires i.e. forked or split the wire. The output cell is placed next to the forked wires which causes the switching of the cell adjustment. The corners of the cells must be touched to switch the electrons. The adjustment of cells is like that cell corners should be touching right and left of the fork.By this arrangements of cells, output will be inverted. Hence this will produce the value as a 1 and 0 at the output and vice versa.

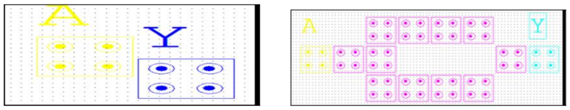


Fig. 8. QCA INVERTER

QCA AND Gate

AND gate is the basic logic gate used in digital design system. QCA AND gate is designed using single majority gate and simulate in QCA designer tool.The output is depends on the input polarization. Figure shows the three input AND gate in which A and B are two input and C is the control line.

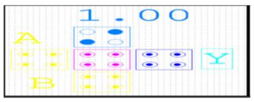


Fig. 10. QCA OR Gate

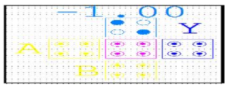


Fig. 9. QCA AND Gate

QCA OR Gate

Design of OR gate in QCA is similar to the design of AND gate just make difference in the control line polarization.Figure shows the OR gate in which control line is set to binary 1.The output is based on the majority of the input cells and control line.

QCA NAND Gate

QCA NAND Gate is constructed by connecting simple QCA NOT Gate to the QCA AND Gate.Figure 11 shows simple QCA NAND Gate.

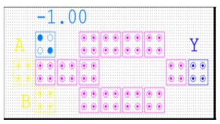


Fig. 11. QCA NAND Gate

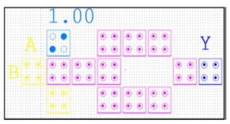


Fig. 12. QCA NOR Gate

QCA NOR Gate

The structure of QCA NOR Gate is taken by connecting QCA OR Gate and Invrter.Figure 12 shows simple QCA NOR Gate.

Results

The simulation of proposed inverter has been checked by exhaustive verification designs. It is simulated and tested using QCADesigner tool and is shown in Figure First figure shows the simulation of INVERTER using two QCA cells while another one represents the simulation of INVERTER using nine QCA cells.

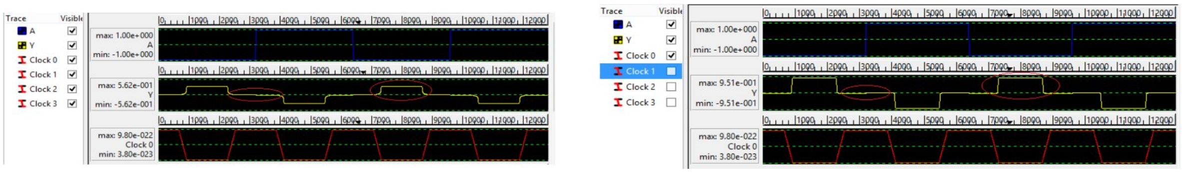


Fig. 13. Simulation of QCA INVERTER

The performance of simple two cell inverter implemented in this work is compared with that of the nine cell inverter. The results have been found to test the proposed implementations in terms of area, circuit complexity (No. of cells) and latency (clock delays). The simulation result of QCA AND gate is shown in figure 14. Simulation is done with QCA designer tool which gives more accurate output.The output shown here is based on input polarization.

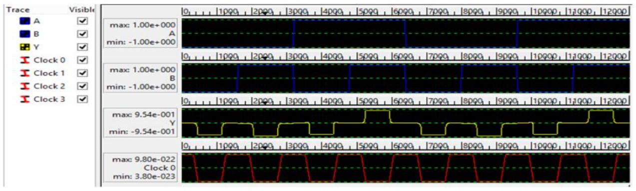


Fig. 14. Simulation of AND Gate

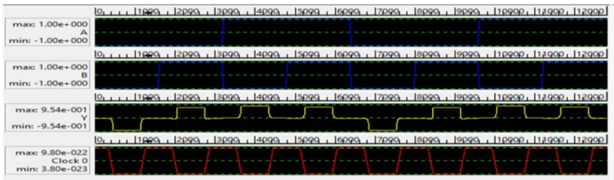


Fig. 15. Simulation of OR Gate

Figure 15 shows the simulation result of QCA OR gate. Output can be varies with respect to the input polarization and control line C.

By using this QCA AND gate and OR gate any combinational circuit can be designed with minimum number of cells. Following figure 16 and 17 shows simulation of QCA NAND Gate and QCA NOR Gate.

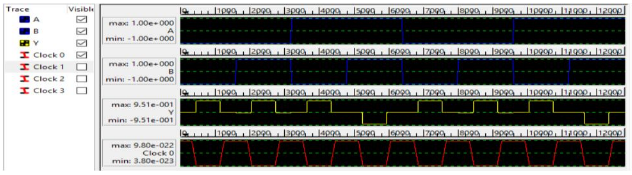


Fig. 16. Simulation Of QCA NAND Gate

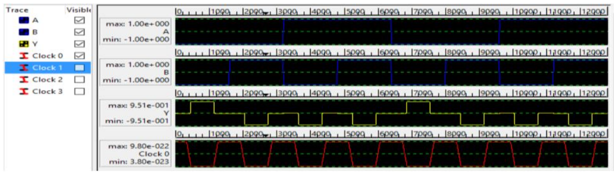


Fig. 17. Simulation Of QCA NOR Gate

Thus the QCA designer tool performs any digital circuit with minimum complexity and gives accurate simulation. This paper describes some combinational designs and performs simulation of these designs.

Conclusion

This paper reviews the paradigm of QCA and some emerging technologies are mentioned. Some limitations to the adoption of technology are described. It is likely that the QCA technology is one of the alternative over some recent technologies in terms of speed and power consumption. QCA nano technology is used in quantum computing to design any electronic system. The propose design will be used to implement circuits based on logic operations like combinational circuit design. Here in this article, the performance of QCA inverter is shown using QCAD tool. And the simulation results are more accurate in terms of speed, latency. Hence, the proposed design architecture is the better alternative to CMOS technology and will be used to achieve the goal of low power dissipation and high performance in QCA technology over other technology.

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