

Trade off between speed and defect tolerance of QCA designs in the Presence of different manufacturing defects

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Abstract

Quantum-Dot Cellular Automata (QCA) is one of the most promising nanotechnologies that advance the current CMOS VLSI technology to a new era. In our earlier work [1], it was found out that the third level of design hierarchy that is Place and Route (P&R) stage holds the key for resolving design for performance issue in case of various QCA circuits. However to operate at room temperature, the diameter of a quantum-dot must be reduced to approximately 10 nanometer. Such a nano scale design requirement poses great challenge in manufacturing QCA systems. There are several manufacturing processes for QCA systems, among them self assembling monolayer (SAM) has gained the most popularity. Within SAM depending on the choices of molecules, the manufacturing processes vary which in turn make the QCA systems prone to different types of defects in different extent. As the chance of occurrence of different defects varies from one manufacturing process to another, in this work it has been intended to see how optimized QCA designs perform in the presence of these manufacturing defects i.e. to find the tolerance level of the QCA designs where clock zones have been optimized for speed. The traditional QCA design has been compared with the optimized (in terms of clock zone) QCA design in the presence of most common manufacturing defect namely cell omission. It has been observed that when cell omission defect is more likely, traditional QCA designs are more robust compared to the faster ones. However it will be demonstrated that the proposed design optimization methodologies found in this work can generate a QCA implementation, not only faster but also defect tolerant. A QCA full adder has been chosen as an example for this analysis.

1. Introduction

INTEL co-founder, Gordon Moore, predicted that the packing density of IC chips would double every two years, and his law was more or less followed for the last fifty years. However, it seems that further reduction in device size will generate quantum mechanical effects that hinder the device's proper operation. With an eye toward the demise of the transistor, many molecular sized devices are being investigated for their feasibility as an electronic building block. Among them, Quantum-dot cellular automata (QCA) [2, 3, 4, 5] is one of the most promising nanotechnologies. It attempts to create general computational functionality at the nanoscale by controlling the position of single electrons. More about fundamental of QCA and how to design a circuit using QCA will be introduced in Section 2.

In our prior work it has been shown that the optimization of clock zone can result faster QCA designs. However in the nanometer range, defects are very likely to occur. In the presence of manufacturing defects how the traditional and optimized QCA designs perform, has been analyzed in this work. It has been observed that in the presence of the most common manufacturing defect that is 'missing cell' defect, traditional design style proves to be more robust than the optimized design style. However new design guidelines have been presented in this work which result faster and robust QCA design at the same time.

In the following, during a brief review of QCA circuit properties in Section 2, we highlight the differences between QCA-based logic designs and traditional CMOS designs. It is then followed by the description of different QCA manufacturing defects in Section 3. Analysis of performance of traditional and optimized QCA full adder in presence of 'missing cell' defect is presented in Section 4 and 5. Section 6 focuses on the alternative design styles that result faster and defect tolerant QCA design at the same time.

2. Fundamentals of QCA

Quantum-dots are nanostructures created from standard semi-conductive materials such as InAs/GaAs. The fundamental unit of QCA is the QCA cell created with four quantum-dots positioned at the vertices of a square. Each QCA cell is charged with two mobile electrons, which may tunnel between adjacent quantum-dots if potential barrier between dots is low. These electrons tend to occupy antipodal sites within a cell as a result of their mutual electrostatic repulsion. By providing tunneling junctions with potential barriers controlled by local electric fields that are raised to prohibit electron movement and lowered to allow electron movement, an isolated cell can have one of the following three states, null, binary 1 and binary 0. A null state occurs when the barriers are lowered and the mobile electrons are free to localize on any dots. The other two states are polarizations that occur when the barrier is raised, and serve to minimize the energy states of the cell. These two states provide a natural digital decoding of logic states '1' and '0' and are denoted as $P=+1$ (binary 1) and $P=-1$ (binary 0) as shown in Figure 1.

QCA transfers information by the Coulombic interaction of electrons trapped in quantum-dots [3], rather than the electron flow. It is done by the electrostatic effect of neighboring cells to lift the degeneracy and result in a new logic state of the target cell. If one cell at the end has a fixed polarization, all cells along the QCA wire has the same polarization based on the Coulombic interaction. Note that the inter-cell interactions do not result in any current flow and power dissipation from the internals of a cell. In addition, QCA wire [6] is made of QCA cells and participates in logic operation as well. Unlike CMOS technology, there is no concept of metal layers. Wire crossing using coplanar or multi layers must be carefully designed. Off-center wiring is possible for normal, weak, or even inverted polarization.

The basic logic gate in QCA is the majority gate [3], consisting of five QCA cells in a cross pattern, with three inputs and one output. By fixing a single input to 0, a 2-input AND gate can be implemented, where as fixing to 1, a 2-input OR gate is implemented. The constant 0 and 1 can be created during the manufacturing process and do not require to be routed to common ground and power source. The majority function is not universal and hence requires inversion, which can be done by off-center wiring.

QCA Clocking: QCA clocking [4] provides the electric field for signal propagation and plays a key role in controlling QCA functionality. Unlike standard CMOS clock, QCA clock is not a "signal" which has just a low and high phase. It is rather a representation of the four phases of inter-dot potential barriers, where each clock is shifted in phase by 90 degree. When the clock is high, i.e., the electrical field barrier is low, a cell is relaxed and has no polarization. When the clock is low, i.e., the electrical field barrier is high, a cell is latched with the polarization determined by its neighbors. In between these two states, a cell is either latched or relaxed.

A group of QCA cells that receive the same clock is referred to as a 'clocking zone'. The clock zones are physically adjacent, so that information exchange must be performed from one to the next in sequential order. Such a behavior can be considered as a sequence of D-latches. This allows information to be 'pipelined' through the circuit as a result of the successive latching and unlatching in cells connected to consecutive clock zones. As a result, the latency of a QCA circuit is determined by the numbers of clock cycles (or clock zones) along its critical path.

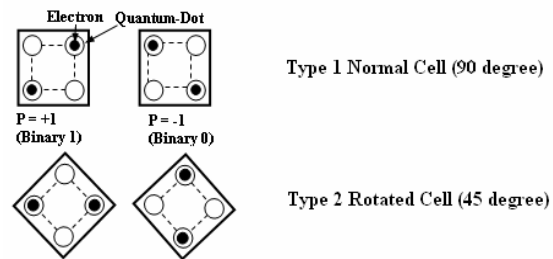


Figure 1: QCA Cell and its states

According to the above mentioned QCA basics, the followings are three key observations to design a QCA circuit:

1. QCA clocking makes a QCA design composed of D-latches, which is suitable for pipelining architecture.

2. QCA clocking has four phases in a cycle. Proper synchronization is required for all input signals of a gate to arrive simultaneously, which in turn is tightly related to the proper QCA clock zone assignments.

3. As the performance of a QCA design depends on the number of clock zones between any pair of signal points, a QCA design with less number of clock zones should have better performance. Hence,

aggressive placement and route is the key to improve the performance of a QCA design.

3. Review of the Various QCA Defects

At the nanometer level, various types of defects are likely to occur during the manufacturing of the nanoscale devices. Before the performance of QCA full adder is analyzed in presence of the defects, it is essential to learn about the manufacturing process and the defects that are likely to occur during this process.

3.1 Manufacturing of the QCA Devices

The early QCA cells and other simplified structures were manufactured by using metal dot cells. Basically metal dot system using Al islands with Al/AlOx/Al tunnel junctions were pioneered by Fulton & Dolan. An individual QCA cell was built and tested using their technique in [7].

The metal dot systems have several associated downsides. These devices operate only at liquid helium temperatures because the metal islands suffer from relatively large capacitances lowering the charging energy. So people were more interested to investigate the potential for molecular QCA systems. The first molecular QCA device was reported in [8]. The molecular QCA systems are likely to be manufactured via self assembly process. The process proposed to attach candidate molecules to a substrate, first grows a SiO₂ layer, uses electron-beam lithography (EBL) to create trenches where QCA molecules are attached, and then soaks the wafer in a bath containing QCA molecules [9].

3.2 Possible Defects during the Process

A likely defect for any molecular electronic device is displacement. For QCA, a displacement would occur when the cell did not attach precisely in the desired location. Displacement also needs to be considered because even if the molecules align precisely as desired in trenches, it appears that they will still have surface attachment angles that vary molecule to molecule [10]. Although various lithographic techniques, such as lit-off, imprint, e-beam, have been proposed for nano electronic circuits, they will introduce the defect resulting from the removal of resist. For a molecular QCA system, this will cause either missing cells (resist not fully removed) or excess cells (too much resist removed). Additionally, there is possibility that all desired cells may not attach as desired. All of these defects

[11] that can result during manufacturing process can be modeled in QCA Designer tool as presented below.

1. Cell displacement defect

The defective cell is displaced from its original position. In Figure 2(b) the cell A is displaced from its original position as shown in Figure 2(a).

2. Cell misalignment defect

The defective cell is not properly aligned. In Figure 2(c) the cell A is misaligned from its original position.

3. Cell omission defect

The defective cell is completely missing as compared to the defect free case. In Figure 2(d) the cell A is completely missing.

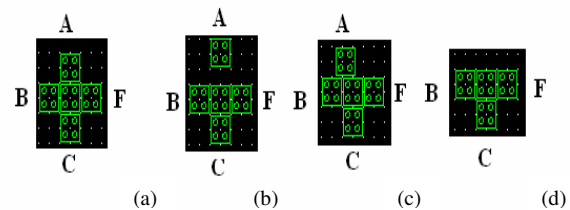


Figure 2: Various cases of defect

Apart from these three types of defect, cell overlapping defect and cell with missing dots can also take place during manufacturing process. However QCA manufacturing processes have not yet reported these two types of defects to the QCA community.

4. Cell overlapping defect

Multiple cells can overlap one over the other.

5. Cell with missing or excess dots

During manufacturing it can happen that instead of normal four dots, cell with fewer or greater than four dots results. This will certainly cause the design to malfunction.

This work focuses on how the proposed performance-optimized QCA full adder design [1] will perform in presence of these defects, mainly the missing cell defect which is very likely to occur during manufacturing process.

4. Effect of Missing Cell Defect on Faster Adder Design

Most popular manufacturing method for molecular QCA system is SAM (self assembling monolayer). However, due to the usage of different

materials in SAM, the surface attachment angle varies quite significantly [10]. The phosphonate terminated surface gives surface binding angle less than 30 degree, where as when a hydroxyl terminated surface is used, it gives the binding angle ranging from 35 to 52 degree. Due to the variation of this surface binding angle the missing cell defect is very common during manufacturing process. In this paper four classes of missing cell defects have been identified and discussed with regard to their effects in QCA designs. The proposed full adder in [1] is taken as an example to demonstrate the robustness in the presence of the missing cell defect.

4.1 Class 1: Critical Cell near Bend

If any cell is missed at the corner of the design, due to the half cell displacement concept discussed in Section 2, inversion will take place and the design will fail to function properly. Figure 3(b) depicts the scenario. The output waveform (Figure 4) stands for the malfunctioning of the optimized full adder which has been taken as an example in this case.

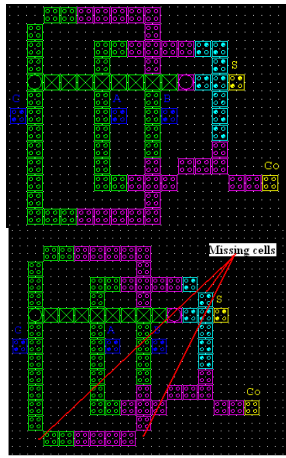


Figure 3: (a) Original Design (b) Design with Missing Cell

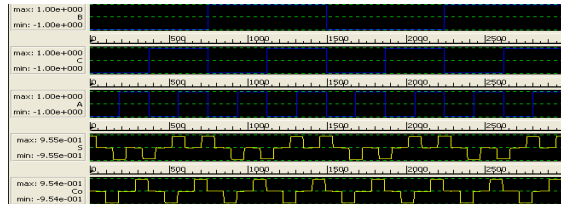


Figure 4: Simulation Result of QCA Full Adder with Missing Cells

4.2 Class 2: Missing Cell in the Non-Critical Clock Zone

According to the proposed heuristics in [1], no additional clock zone needs to be allocated for the area where the output of a majority function is generated. Non-critical clock zone is defined as any clock zone applied to the area where the desired majority function output is independent of. For example in Figure 3(a), in the first clock zone i.e. in the green region, no majority function output is determined hence it can be referred as non-critical clock zone.

Along the direction of the signal propagation within the non-critical clock zone if only one cell is missed, the proper output is still obtained. The missing cell contributes to the lowering of the kink energy and the propagation time of the signal. But the delay and low energy level associated with only one missing cell in the non-critical zone does not have sufficient influence for making the design nonfunctional as verified by the mathematical equation for relative kink energy calculation below.

$$E_{kink} \propto (1/r^5) * \cos(2(\theta_1 + \theta_2))$$

Here r is the relative distance between cells; θ_1 and θ_2 represent relative displacement angle between cells.

The QCA optimized full adder design is taken as an example to demonstrate the ineffectiveness of a single missing cell in non-critical clock zone. The QCA full adder layout, with multiple single missing cells with no two cells are in the consecutive locations and each single missing cells is at least 3 cells apart, is shown in Figure 5(a). The design operates correctly as it is evident from the simulation waveform presented in Figure 5(b).

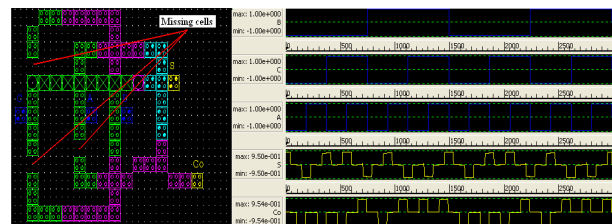


Figure 5: (a) QCA Layout (b): Simulation with missing cells waveform

4.3 Class 3: Two or More Consecutive Missing Cells

If two or more consecutive cells are missed in any clock zone, the design fails to operate properly. Due to the additional delay and weakening of the energy level enforced by two or more missing

cells, the design fails to operate correctly. This fact has been demonstrated in Figure 6, by taking the example of an optimized full adder. However, if an additional clock zone is added in the majority output area, the missing of two consecutive cells in the non critical clock zone can still keep the design functional. The fact will be discussed in more depth in the Section 5.

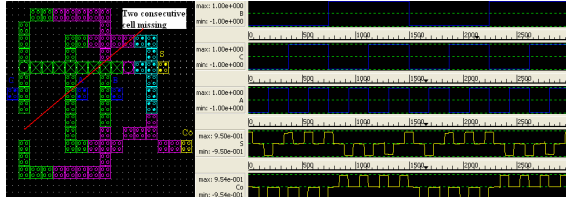


Figure 6: Layout and Simulation Result of QCA Design with two Consecutive Cell Missing

4.4 Class 4: Missing Cells in Critical or Transition Zone

By the application of the heuristics as presented in the previous work, if additional clock zone requirement is eliminated then the clock zone, where the majority output is determined, is defined as critical clock zone. Even if a single cell is missed in the critical clock zone the design fails to produce the true output. The delay and loss of energy as mentioned in subsection 4.2 causes this situation to arise. Moreover if a cell is missed in the transition zone i.e. the juncture of critical and non critical clock zone, the design produces erroneous output. The phenomenon has been depicted in Figure 7(a) and Figure 7(b). The simulation waveform shown in Figure 8 confirms that both the designs fail to produce true output. However different design style can still maintain the circuits to function properly in the presence of these defects. Such an alternate design style will be discussed in the next Section.

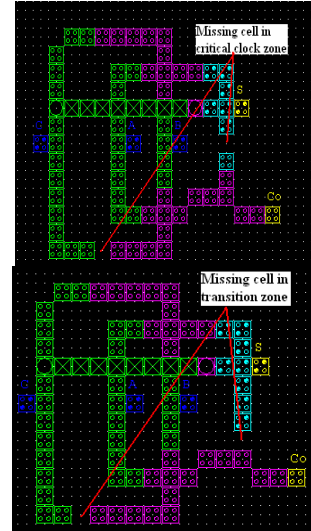


Figure 7: (a) Missing Cell in Critical Clock Zone
(b) Missing Cell in Transition Zone

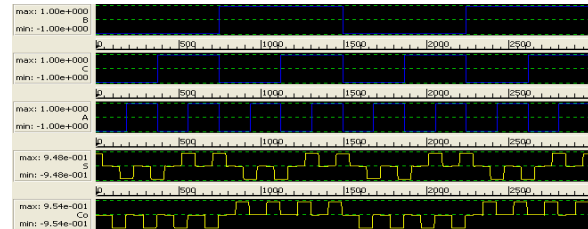


Figure 8: Simulation Result of Designs with Cell Missing in Different Zones

5. Effect of Missing Cell Defect on Traditional Adder Design

Though the QCA full adder design discussed in Section 4 is faster (requires 3 clock zone) in comparison to the traditional QCA full adder (requires 4 clock zone) designs, the robustness in presence of missing cell defect is somewhat compromised. Two cases will be cited to show that the traditional QCA design is more robust in comparison to the optimized QCA design.

The reason is because an extra clock zone is added near the majority gate for the traditional case. The extra clock zone helps to recover the delay and loss of energy due to the missing cell. In Figure 9, the traditional QCA full adder layout is presented with cells missing at the transition zone. However, the circuit still operates properly. Though the delay is added in the signal propagation line but the additional clock zone applied on the five cross patterned cell near the majority function, overhauls the delay factor and keeps the circuit operational.

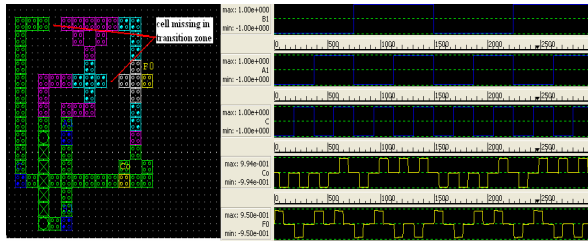


Figure 9: Layout and Simulation Result of QCA Full Adder with Missing Cell near Transition Zone

In the non-critical clock zone, two consecutive missing cells make the optimized QCA full adder circuit to malfunction as stated before. However for the traditional QCA full adder design, missing of 3 or even 4 consecutive cells can keep the circuit functional. The reason is the presence of extra clock zone which recovers the delay and loss of energy due to the missing cells. In Figure 10, it is shown that the traditional QCA full adder with 3 consecutive missing cells in the non-critical clock zone operates correctly.

The two cases described above show that the traditional QCA design is still robust compared to the faster optimized QCA designs. However, it will be investigated in the next Section that whether it is possible to make the QCA designs faster and robust at a time.

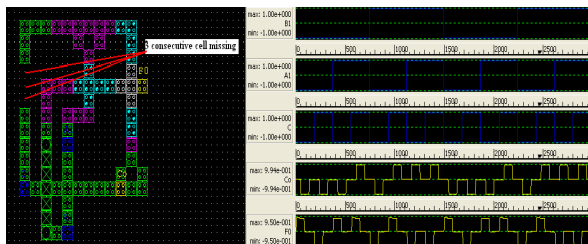


Figure 10: Layout and Simulation Result of QCA Full Adder with Three Consecutive Missing Cells

6. Thick Multi-line Robust Optimized QCA Design

It has been shown that the faster full adder design is not very robust in the presence of the missing cell defects. If a single cell is missed in the critical clock zone or in the transition zone, the design fails. More than one consecutive missing cell in the non critical zone also makes the design non-functional.

However, by adding extra lines to the input lines of the majority gate, it is possible to make the design more robust in presence of the defect. The reason can be explained as follows.

Addition of one or two extra line provides the design with alternative path for signal propagation where no cells are missed. At the same time additional cells are used for the purpose of positive feedback which helps to recover the lost energy during the cell miss.

To show the improvement in robustness, the optimized QCA adder has been taken as an example. The double line faster QCA full adder is shown in the Figure 11(a). In Figure 11(b) several missing cell cases have been outlined. It is seen that though cell is missed in the transition zone, critical zone, design still operates correctly. It is also observed that with the three consecutive missing cells in the non-critical clock zone, design remains functional. The simulation waveform shown in Figure 12 supports the true operation of the faster robust QCA full adder in presence of those missing cell defects.

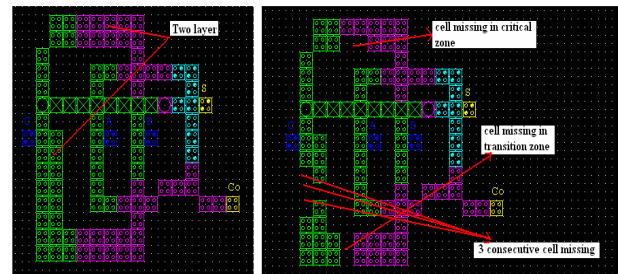


Figure 11: (a) Double Missing Cell line Full Adder
(b) Different cases

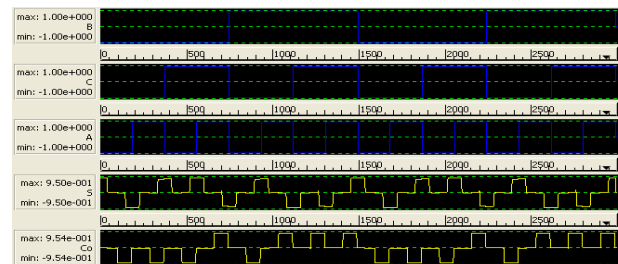


Figure 12: Simulation Waveform of Robust Faster QCA adder

Thus application of the thick- multi line design technique to the faster full adder makes it more robust. The improvement in robustness has been presented in Table 1. It clearly shows that for the three classes of missing cell defect the robust optimized full adder obtained during this work functions properly

<i>Design</i>	<i>Missing cell in the Critical zone</i>	<i>Missing cell in the Transition zone</i>	<i>2 consecutive missing cells in non critical zone</i>
Optimized full adder (Fig 3(a))	Fail	fail	fail
Robust optimized full adder(Fig 11)	Work	work	work

Table 1: Effect of Missing Cell Defect on Optimized and Optimized Robust QCA Full Adder

7. Trade-off between Traditional and Thick Multi-line Design Style

Though thick multi line design style results more robust QCA design in comparison to the traditional one. There are few things which should be considered when designing circuits using this new technique.

1. In multilayer design style, number of cell count of the QCA design increases. More cells mean more defects that are likely to occur in the circuit. However, in QCA manufacturing with the increase of cell count the rate of increase of defects is very low.
2. The area requirement increases when designing QCA circuits using multilayer design style which in turn can make the routing more congested.
3. The more congested routing or the presence of multiple layers can also create the possibility of shorting in the QCA circuit design. However, it is too early to comment on the road blocks of the thick multi line design style before it is put into the manufacturing process.

8. Conclusion

The defects for QCA circuits that are likely to occur during the manufacturing phase have been investigated in this study. The proposed QCA adder design in [1] has been analyzed in the presence of the most common missing cell defect. It has been observed that the traditional QCA full adder design is somewhat robust in comparison to the QCA full adder constructed by the application of the design techniques proposed in our earlier work [1]. However it has been shown that by the application of certain technique such as multilayer thick line design technique, the robustness of any

QCA circuit can be enhanced. This finding has been applied on the faster QCA full adder design, resulting in a more robust adder structure. So in this paper QCA adder design has been validated which is faster and robust at the same time.

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