Microprocessors and Microsystems 39 (2015) 426–433

Contents lists available at ScienceDirect

Microprocessors and Microsystems

journal homepage: www.elsevier.com/locate/micpro

Design and characterization of a new fault-tolerant full-adder for quantum-dot cellular automata

Razieh Farazkish [a,*], Fatemeh Khodaparast [b]

[a] Department of Computer Engineering, Islamic Azad University, South Tehran Branch, Tehran, Iran
[b] Department of Computer Engineering, Islamic Azad University, Science and Research Branch, Tehran, Iran

ARTICLE INFO

Article history:
Available online 1 June 2015

Keywords:
Quantum-dot cellular automata
Full-adder
Fault-tolerant circuits
Nanoelectronic circuits
Design and modeling

ABSTRACT

A novel fault-tolerant full-adder for quantum-dot cellular automata is presented. Quantum-dot cellular automata (QCA) is an emerging technology and a possible alternative for semiconductor transistor based technologies. A novel fault-tolerant full-adder is proposed in this paper: This component is suitable for designing fault-tolerant QCA circuits. The redundant version of full-adder is simple in structure and more robust than the standard style for this device. By considering two-dimensional arrays of QCA cells, fault properties of such block full-adder can be analyzed in terms of misalignment, missing and dislocation cells. In order to verify the functionality of the proposed device, some physical proofs are provided. The results confirm our claims and its usefulness in designing digital circuits.

1. Introduction

As the current CMOS technology is going to approach fundamental physical limits, there has been extensive research in nano-scale for the future generation ICs. Quantum-dot cellular automata (QCA) is one of the promising new technologies that not only gives a solution at nano-scale, but also it offers a new method of computation and information transformation [1,2]. The superior features of QCA over current CMOS VLSI devices along with the feasibility of designing logic gates, circuits, and massively parallel architectures indicate the potential of QCA as a promising novel computing paradigm. In the sense that it would potentially allow the implementation of massively parallel computing architectures which could outperform the current CMOS VLSI counterparts in every performance aspect, that is, integration density, power consumption, and speed, while also enabling new applications by overcoming inherent limitations of VLSI technology [3].

There are, however, several obstacles for a practical realization of QCA and exploiting full potential of this new technology. Here, it suffices to mention the following issues:

- The first major obstacle is the realization of QCA hardware capable of performing in room temperature. Current semiconductor technologies that are being considered for the QCA implementation would operate only in cryogenic temperatures due to the large size of the cells. This, in turn, has motivated the investigation of molecular realization of QCA. The smaller size of molecules means that Coulomb energies are much larger, so room temperature operation is possible. In fact, there are indicates that realization of QCA-based molecular devices capable of functioning in the current commercial regime is possible. It should be mentioned that the focus of our work is on electronic realization of QCA devices as opposed to magnetic realization. It has been demonstrated that magnetic quantum dots, despite their large size, can operate at room temperature. In Section 2.2, we present a brief overview of the QCA implementation.
- The second obstacle is the means by which input state is fixed and the output state is measured. Obviously, the issue of connecting the nano-world to the micro-world is one that is germane to all type of nano-devices.
- The third issue is the required precision in the assembly and tolerance to fabrication defect. In fact, it is widely believed that QCA devices and circuits will highly sensitive to imprecision in their assembly. Here again it seems that molecular implementation provides an additional advantage by allowing the use of various self-assembly techniques. However, there are still questions as to whether molecular self-assembly techniques would give sufficient control over cell positioning.

In this letter, we will not address the first and second item. We will focus on an approach to overcome some of the issues related

---

* Corresponding author.
E-mail addresses: r.farazkish@srbiau.ac.ir (R. Farazkish), f.khodaparast@srbiau.ac.ir (F. Khodaparast).

http://dx.doi.org/10.1016/j.micpro.2015.04.004
0141-9331/

to the third item. Our approach is based upon considering two-dimensional arrays of QCA cells. Assuming a certain amount of blocks in the assembly of the QCA cells, it is still possible to design circuits that perform the desired functions despite their faulty assembly. This is the direction that we have been pursuing for enabling fault tolerant QCA full-adder.

Two fundamental units of QCA based design are majority and inverter gates; hence, efficient construction of QCA circuits using majority and inverter has attracted a lot of attention [4–15].

A single-bit full-adder can be implemented by using only majority and inverter gates [2,11–12]. As full-adder is the principle element of the arithmetic systems, its performance directly affects the performance of the entire system. Hence, efficiently constructing a full-adder in QCA is of great importance [4,11–13,16–18].

Fault tolerance is the ability of a circuit to continue to perform its tasks after the occurrence of faults. Fault-tolerant design of QCA logic circuits is absolutely necessary for characterization of defective behavior of QCA circuits. In recent years the fault tolerance properties of QCA circuits has been demonstrated by many researchers [3,6,8,9,19–23].

As already mentioned, full-adder is the basic element of QCA circuits; this note investigates a new design for fault-tolerant full-adder that offers remarkable robustness with respect to misalignment, missing and dislocation cells. The presented methods justified based on some physical models. Improving the robustness of the full-adders leads to efficient designing of many fault-tolerant arithmetic circuits.

2. Materials and methods

2.1. Review of QCA

Quantum cellular automata is a new device architecture, which is proper for the nanometer scale. The principle of QCA was proposed by Lent and Tougaw [24]. The basic computational element in QCA is a quantum cell. A quantum cell can be viewed as a set of four charge dots, positioned at the corners of a square. The cell contains two extra mobile electrons, which are allowed to tunnel between neighboring sites [2,25]. The electrons are forced to the corner positioned by columbic repulsion. The two possible polarization states represent logic “0” and “1” as shown in Fig. 1(a) [2,26].

As shown in Fig. 1(b), an ordinary QCA majority gate requires only five QCA cells; three inputs labeled A, B and C, the device cell and the output. The logic function of majority gate is:

$$M(A,B,C) = AB + AC + BC \tag{1}$$

As illustrated in Fig. 1(c), each five-input majority gate must have five inputs and one output [12]. The majority voting logic function can be expressed in terms of fundamental Boolean operator as shown in

$$\begin{aligned} M(A,B,C,D,E) = {} & ABC + ABD + ACD + ACE + ADE + BCD \\ & + BCE + BDE + CDE \end{aligned} \tag{2}$$

Also as shown in Fig. 1(d), each single-bit full-adder can be implemented with only inverters and majority gates. The device has three inputs: two operands a, b, and the previous carry result c. The two outputs are the sum *Sum* and the carry bit *Carry*. Full-adder cells can be easily chained together to produce a multi-bit adder. And in Fig. 1(e) a QCA inverter is shown.

As stated earlier, a QCA array performs computation through Columbic interaction among neighboring cells that causes them to influence each other’s polarization. Therefore, computation with QCA arrays is edge driven, in the sense that both energy and information flow in from the edges of the array only. This also provides the directionality in the computation by the array. In this sense, the difference between input and output cells is simply that inputs are fixed while outputs are free to change [24]. The QCA array then performs the desired computation by reacting to the change in the boundary conditions. The fact that the computation is edge driven implies that no direct contacts to interior cells are made and thus eliminating the interconnection problem. This further implies that the paradigm involves computing with ground states. That is, the QCA array reacts to change in the input and settles to a new ground state, which represents solution of the desired computational problem for which the array is specifically designed. However, computing with ground state implies that the computation is temperature sensitive. In fact, if the thermal fluctuations excite the array above its ground state then the array may produce wrong results. Furthermore, the dynamics of the array is hard to control. Consequently, the setting time to the ground state cannot be controlled or predicted and it would vary depending on the complexity of the array. Also, the array might settle to a stable state, producing wrong result or leading to a significant delay in reaching the true ground state.

In order to overcome these limitations of computing with ground state, a switching scheme has been developed [26]. In this scheme, a QCA array is divided into sub-arrays and a different clock controls each sub-array. The proposed clock scheme for QCA is multi-phased. This clocking scheme allows a given sub-array to perform its computation, have its state frozen by raising its inter-dot barriers, and then have its output as the input to the successor sub-array. Due to the multi-phase nature of this clocking scheme, the successor sub-array is kept in an unpolarized state so it does not influence the calculation of preceding sub-array. Such clocking scheme implies a pipeline computation since different sub-array can perform different parts of the computation. In this sense, QCA arrays are inherently suitable for pipeline and systolic computation.

2.2. QCA implementation

There have been several proposals for physically implementing QCA [2,26–32]. In this section, a brief background on metal, molecular, and magnetic QCA is provided:

2.2.1. Metal QCA

Micro-sized QCA devices have been fabricated with metal. This device is composed of four aluminum islands (as dots) connected with aluminum oxide tunnel junctions and capacitors. The area of the tunnel junctions determines the island capacitance (the charging energy of the dots) and hence, the operating temperature of the device. The device has been fabricated using Electron Beam Lithography (EBL) and dual shadow evaporation on an oxidized silicon wafer. Experiments have confirmed that switching of electrons in a cell can control. A semiconductor implementation of QCA is advantageous due to well understood behavior of existing semiconductors for which several tools and techniques have been already developed. However, fabrication processes are not suitable to mass produce QCA cells of sufficiently small dimensions for operating at room temperature.

2.2.2. Molecular QCA

As an alternative technology, molecular QCA has several advantages over metal dot QCA; small cell size (density of up to 10^{13} devices per cm^2), a simple manufacturing process, and operation at room temperature are some of the desirable features of molecular QCA. Moreover, an improvement of switching speed by 100 times in molecular-sized QCA cells has been reported over semiconductor QCA cells. A further advantage of molecular QCA is that cells are structurally homogeneous down to the atomic level. In initial analysis of a simple molecular system, each molecule