Microelectronics Journal 47 (2016) 7–18

Contents lists available at ScienceDirect

Microelectronics Journal

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

On the reliability of majority logic structure in quantum-dot cellular automata

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ARTICLE INFO

Article history:
Received 22 July 2015
Received in revised form
6 November 2015
Accepted 7 November 2015
Available online 11 December 2015

Keywords:
Quantum-dot cellular automata (QCA)
Reliability
Fault tolerant logic
QCA tiles
QCA defects
Majority voter

ABSTRACT

Quantum-dot cellular automata (QCA) is projected to be a promising nanotechnology due to its extremely small feature size and ultra low power consumption. However, acceptance of a QCA design is limited due to its high defect rate. Efficient fault tolerant schemes are, therefore, needed for reliable design. This work targets design of a new fault tolerant scheme around QCA logic primitives which encapsulates two different orientations of QCA cell. A 2×2 array of four rotated ('+') cells, called complementary tile (CT), is introduced to maximize the throughput. It ensures 100% fault tolerance under single cell missing defect. Two reliable majority voters (RMV), based on the CT, are designed which outperforms the existing majority logic in QCA. The functional characterization and polarization of RMV under different cell deposition (missing/additional) defects are covered. The significance of the clocking in fault tolerance is also investigated with RMV with multi clock zone. The error probability model for the proposed RMV, under cell deposition (missing/additional) defect, is developed to ensure better understanding of reliability in QCA.

1. Introduction

As CMOS devices reach their fundamental limits, they will increasingly suffer from lower design tolerances and fabrication variability, which have negative impacts on reliability and result in increased device failure rates. These future limitations of CMOS have led many to consider novel nanometer-scale devices that are expected to have faster switching speed, lower power consumption, and better scaling characteristic [1]. Quantum-dot cellular automata (QCA) have emerged as one of the promising new technologies for future generation ICs that overcome the limitation of CMOS [2]. In QCA, information is transferred and transformed by Columbic interactions among basic elements (referred to as cells) rather than electrical currents as in CMOS-based VLSI. So the position of a cell in the logic gate/circuit is very important as it may result in erroneous output.

Two arrangements of quantum-dot within a cell referred to as the 90° ('×') normal cell and the 45° ('+') rotated cell can be utilized to compute the binary information. The rotated cell is identical in all ways to the standard cell except it is rotated by '45°' [2,3]. The fundamental unit of QCA based design is the 3-input majority gate. Due to the functional incompleteness of majority logic, an additional inverter is mandatory for majority gate to constitute the universal minority function. Rigorous research is going on towards the implementation of complex logic structure in QCA which can be viable for alternative current CMOS [4–16].

According to [17], the predictable huge complexity of nano architectures enforces the requirement of a high fault tolerance. QCA also confronts the challenges of many defects which is first explained in [18,19]. Though other fault like stray charge and rotational defect may also occur in QCA logic, the cell misplacement (cell misalignment, presence/absence of a cell) has been identified as the prime source of defect for QCA because the process of cell deposition is very sensitive. The importance of the reliability of majority voter stems from its use as logic primitives in fault-tolerant architectures around QCA [20,21].

Several attempts are made to realize fault tolerant structure around majority logic [22–28]. To achieve a reliable architecture, QCA tiles with redundant cells are identified as prominent one. This approach ensures at most 67% fault tolerance under single cell missing defect [21,20]. Realization of coplanar wire-crossing using both 45° cell and 90° cell, as in [30], is difficult, but such restriction can be averted with the introduction of clock zone based approach as described in [31,4]. The fabrication issue related to cell

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http://dx.doi.org/10.1016/j.mejo.2015.11.002
0026-2692/

placement of rotated and non-rotated cell towards the realization of coplanar wire-crossing is addressed in [4].

On the other hand, Von Neumann proposes probabilistic characteristics of a system in which each component can fail independently with a probability of ε [32]. Neumann states that a system built with unreliable components can compute reliably when ε is sufficiently small. In general, a reliable system is defined as one that performs computation with a probability of output error less than $1/2$. When the probability of output error reaches $\frac{1}{2}$, the results of computation become irrelevant to the inputs and restoration of the outputs to correct signal values is not possible.

In this context, we attempt to design reliable QCA logic primitives that can ensure highly fault tolerant QCA designs, under different cell deposition (missing/additional) defects. The issue of fault tolerance has been so far analysed from an implementation technology point of view [17,33] and very few on architectural point of view [27,28]. In this paper we study the issue of fault tolerance from an architectural point of view. At this point, designing QCA is an “in-principle” activity meant to explore what might be possible if and when the fabrication issues are overcome [3]. This work focuses on the architectural issues associated with cell deposition (missing/additional) defects which occur during manufacturing of circuits. The major contributions of this work around reliable QCA architecture can be summarized as follows:

- This paper investigates a new design of the tiniest QCA tile structure (2×2) with hybrid cell (cell with ‘$\times$’ and ‘$+$’ orientation), called complementary tile (CT). The reliability of the QCA structure CT is reported.
- Based on the proposed QCA CT, a new reliable majority voter (RMV) is developed which achieves a high degree of robustness in terms of misalignment, missing, and dislocation of cells. The effectiveness of the design is established as physical proofs as well as through simulation.
- Detailed characterization of functional properties of the proposed logic is described.
- Estimation of error-reliability trade off of a QCA circuit is explored with error probability model.
- It is established over the other existing implementations that the proposed majority gate (RMV) demonstrates significant improvement in terms of area, complexity, and robustness.

This paper is organized as follows. Section 2 deals with preliminaries including a brief overview of QCA technology. Related works on the fault tolerant architecture are explored in Section 3. The proposed design of complementary tile is introduced in Section 5. In Section 5.3, the performance of proposed CT is reported. In Section 6, a reliable architecture of majority voter based on CT is presented. The reliability of the proposed RMV is analyzed in Section 7 followed by the introduction of error probability metric around RMV, to measure its reliability, in Section 8. Simulation and framework is elaborated in Section 4. The conclusion is in Section 10.

2. QCA basics

A QCA cell consists of four quantum dots positioned at the corners of a square (Fig. 1(a)) and contains two free electrons [34]. The two free electrons can quantum-mechanically tunnel among the dots and settle either in polarization $P=-1$ or in $P=+1$ as shown in Fig. 1(b). A QCA cell with polarization $P=-1$ denotes logic 0 state. On the other hand, polarization $P=+1$ defines the logic 1 state of the cell. Timing in QCA is accomplished by the cascaded clocking of four distinct and periodic phases [34,4] as shown in Fig. 1(f).

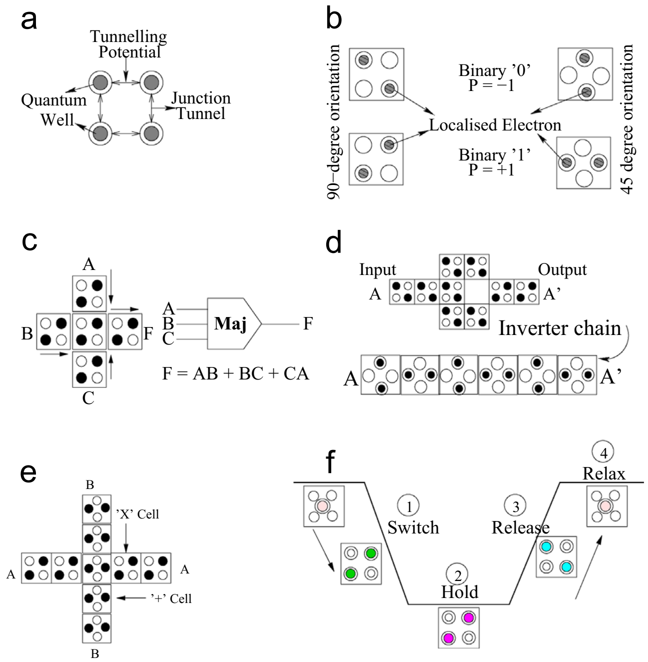

Fig. 1. QCA basics. (a) Structure of a QCA cell. (b) QCA cell with two polarization. (c) Majority voter. (d) Inverter. (e) Wire-crossing. (f) Clocking.

The basic structure in QCA is the 3-input majority voter, MV(A, B,C)=AB+BC+CA (Fig. 1(e)). It can also function as a 2-input AND or a 2-input OR logic, if one of the three input cells is fixed to $P=-1$ or $P=+1$. The QCA inverter realized in two different orientations is shown in Fig. 1(d). Using simple chain of rotated cell (45°)/+-cell an inverter chain can be realised as shown in Fig. 1(d). In QCA based logic, two kinds of wire crossover, called coplanar crossover and multilayer crossover, are possible. Due to the fabrication constraints, multilayer wire crossing is not explained here. Fig. 1(e) describes the co-planar wire crossing considering a 90° ($\times$-cell) and a 45° (+-cell) structure.

The position of the electrons can be found out using Eq. (1). The state energy is found out by calculating electrostatic energy between each cell and its adjacent cell. Electrostatic energy between two quantum dots in cell i and cell j is calculated as shown in the following equation [35]:

$$E_{i,j} = \frac{q_i q_j}{4\pi\varepsilon_o \varepsilon_r |r_{ij}|} \tag{1}$$

where, ϵ_0 is the permittivity of free space and ϵ_r is the relative permittivity of the material of the quantum cell. q_i and q_j are the charges of the electron dots at i and j and the distance between the two dots is given by $r_{i,j}=|r_i - r_j|$. The above equation is used to calculate the electrostatic energy of the electrons inside faulty device cell for every different input. The configuration having the minimum energy for a particular input is considered to be the most stable orientation.

Kink energy: The energy of the cell can be calculated by summing over kink energy of all dots in each cell. The Kink energy between two adjacent cells is defined as the difference in the electrostatic energy between the two polarization states. The kink energy between the two cells ’i’ and ’j’, $E_{i,j}$, is calculated by keeping ’i’ in its original state (constant) and ’j’ in the two different polarization states, and then finding the difference between these two energies:

$$E_{kink} = E_{opp.\ polarization} - E_{same\ polarization}$$
$$E_{i,j} = E_{i,j\ opp.\ polarization} - E_{i,j\ same\ polarization}$$