Introducing Interconnection Crossing in Ternary Quantum-dot Cellular Automata

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***Abstract*—The ternary Quantum-dot Cellular Automaton (tQCA), a processing platform based on interacting quantum dots, was demonstrated to be a promising paradigm for multi-valued processing. With the development of the ternary functionally complete set of elementary logic primitives and the ternary memorizing cell the design of complex processing structures is becoming feasible. Hence, the research focus is moving from the bottom-up design approach to the logic design approach. With the increase of processing functionality there comes also the increase in design complexity. Due to the specific tQCA cell geometry one of the most problematic area tends to be the interconnection crossing. This paper introduces a solution using a multi-layer approach.**

***Keywords*-ternary Quantum-dot Cellular Automaton, tQCA interconnection, tQCA wire, tQCA interconnection crossing, multi-layer design**

I. INTRODUCTION

The Quantum-dot Cellular Automaton (QCA) is perceived as one of the promising computing paradigms, which could be a solution to the technological limitations of the CMOS platform [1]. Its novel concept of operation where information is encoded in charge orientation lets information transmission and processing to be carried out by the same entities, named QCA cells [2].

The promising results in the binary domain have encouraged the research of possible implementations in the realm of multi-valued logic [3]. The redesign of the binary QCA (bQCA) cell, called ternary QCA (tQCA) cell, allowed the representation of three logic values [4]–[6] and the adaptation of adiabatic pipelining was used to solve the issues of the tQCA logic primitives [7], [8]. Hence, the adjustments were made to preserve the operation mechanics and design rules that were extensively researched in the binary domain [9]–[12].

Ternary logic is defined as a generalization of binary logic so one cannot simply use the binary functionally complete set [13]. Therefore chain-based Post logic [14] was used as the foundation of the tQCA implementation of a ternary functionally complete set. The set comprises the ternary majority gate, used to obtain conjunction and disjunction, and the ternary characteristic functions. While the majority gate was implemented using proven approaches from bQCA design [8], this was not the case for the characteristic functions. They were developed following the bottom-up approach, i.e., by observing the behavior of simple tQCA segments and their subsequent composition according to physical design rules [15]. The existence of a functionally complete set made the design of the basic ternary memorizing cell possible [16].

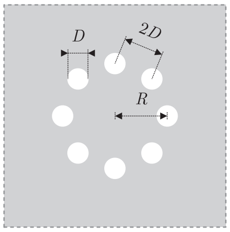


Figure 1. The geometry of the ternary quantum-dot cell.

The described ternary building blocks promote composition of complex ternary processing structures following a logic design approach. However, the research results from the bQCA domain show that efficient design highly depends on effective solutions of building block interconnection [17]. The currently developed basic tQCAs are constrained to remain on a coplanar surface, hence the increase of processing functionality brings also the increase in interconnection complexity. A great deal of it is contributed by crossover problems. Due to specific tQCA cell geometry one of the unique bQCA paradigm features, a coplanar wire crossing, cannot be efficiently implemented in the tQCA domain. This paper presents a study of a possible noncoplanar (multi-layer) approach, which promises an efficient solution of the previously described issue.

Section II starts with a brief overview of the tQCA platform. Section III continues with the presentation of the tQCA wire, the interconnection crossing problem and proposes the multi-layer solution. The conclusion follows in Section IV.

II. TQCA PLATFORM

In general, a QCA is a planar array of quantum-dot (QCA) cells [1]. The fundamental unit of a ternary QCA is a tQCA cell [4]. It comprises eight quantum dots and two mobile electrons. The quantum dots with diameter $D = 10$ nm are arranged in a circular pattern with radius $R = D/\sin(\pi/8)$, so that the distance between neighboring quantum dots equals $2D$ (see Fig. 1). The electrons can only reside at quantum dots or tunnel between adjacent quantum dots, but cannot tunnel outside the cell. The Coulomb interaction

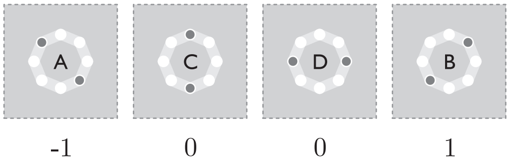


Figure 2. The four possible arrangements of the electrons contained in a tQCA cell that are mapped to balanced ternary values -1, 0 and 1.

between the electrons causes them to localize in quantum dots that ensure their maximal separation (energetic minimal state). The four arrangements, which correspond to the energetic minimal states (ground states), are marked as A, B, C and D (see Fig. 2). The four states can be interpreted as balanced ternary logic values, so A is interpreted as logic value -1, B as logic value 1 and C and D as 0. The arrangement D is typically not allowed (desired) for input or output cells [5]–[7]. The charge distribution in one or more cells in the observed cell's neighborhood, causes one of the four arrangements to become the favored ground state. The cell to cell interaction is strictly Coulombic and involves only rearrangements of electrons within individual cells, thus it enables computation. With specific planar arrangements of cells it is possible to construct logic gates as well as interconnects among them [18].

The reliability of the behavior of a QCA device depends foremost on the reliability of the switching process, i.e., the transition of a cell's state that corresponds to one logic value to a state that corresponds to another and vice versa. It is achieved by means of the adiabatic switching concept, where a cyclic signal, namely adiabatic clock, is used to control the cells' switching dynamic [7], [9]. The signal comprises four phases. The switch phase serves the cells' gradual update of the state with respect to their neighbors. The hold phase is intended for the stabilization of the cells' states when they are to be passed on to the neighbors that are in the switch phase. The release and the relax phase support the cells' gradual preparation for a new switch.

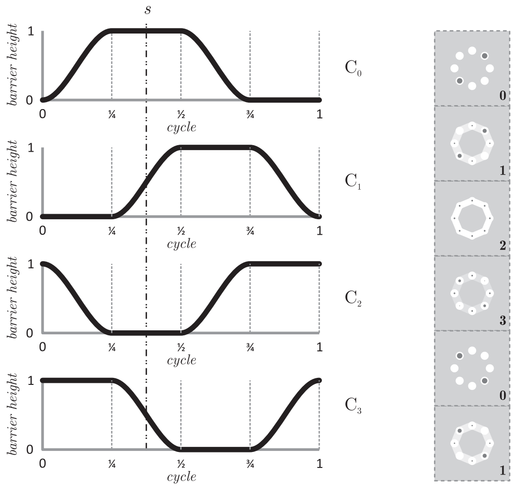
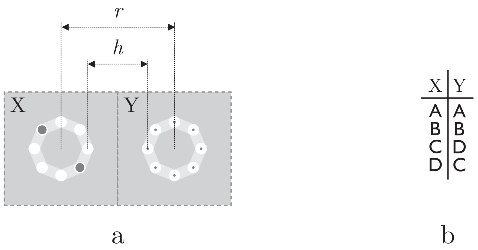


Figure 3. The four phase shifted adiabatic clock signals and an example of the adiabatic pipeline architecture applied to the QCA wire. Let C_0 denote the base signal and C_i, $i = \{0, 1, 2, 3\}$ the base signal phase shifted by i phases.



X	Y
A	A
B	B
C	D
D	C

Figure 4. The coplanar layout of tQCA cells (a) and the result of cell to cell interaction (b).

The correct behavior of tQCA logic gates requires a synchronized data transfer, achievable through a pipelined architecture based on the adiabatic clock [8]. The four phased nature of the clock signal allows any tQCA to be decomposed to smaller stages, or subsystems, controlled by phase shifted signals, each defining its own clocking zone (see Fig. 3). Subsystems that are in the hold phase act as inputs for subsystems that are in the switch phase. A subsystem, after performing its computation locks its state and acts as the input for the following subsystem. As the transaction and processing in the second subsystem is finished it can lock its state while the first prepares for accepting new inputs. With the correct assignment of cells to clocking zones, the direction of data flow can be controlled. Large regions of nearby cells are usually assigned to the same clocking zone in order to eliminate the challenges that would be caused by attempting to deliver a separate clock signal to every cell.

The latency of a QCA circuit is determined by the number of clocking zones along its critical path. A sequence of four clocking zones causes the delay of one clock cycle. Consequently minimizing the number of clocking zones leads to better designs [19].

III. INTERCONNECTION CROSSING

The basic cell to cell interaction shown in Fig. 4a comprises two coplanar tQCA cells, where cell X acts as the input and cell Y as the observed output. Current simulations, based on the Intercellular Hartree Approximation (ICHA) method that uses a tight-binding Hubbard-type Hamiltonian, show that a suitable coplanar intercellular distance for correct state transfer equals $r = 110$ nm, hence the minimum spacing between quantum-dots of neighboring cells is approximately $h = r - 2R = 58$ nm [8]. The interaction result showed in Fig. 4b reveals that the output cell assumes the same state when the input cell's state is A (logic value -1) or B (logic value 1). However, when the input cell's state is C (logic value 0) the state propagates

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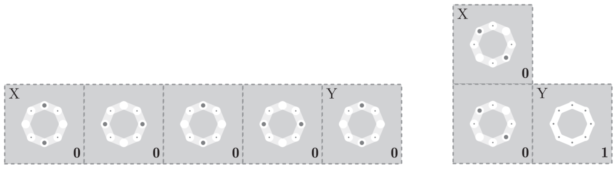
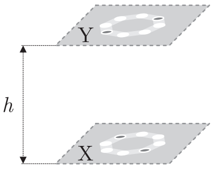


a b

Figure 5. The pipeline architecture for a robust tQCA wire: straight wire (a), corner wire (b).



X	Y
A	B
B	A
C	D
D	C

a b

Figure 6. The noncoplanar layout of tQCA cells (a) and the result of cell to cell interaction (b).

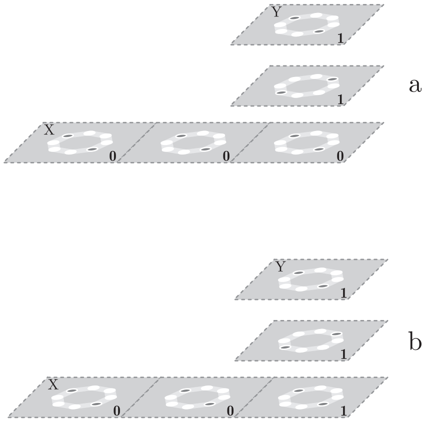


Figure 7. The two possible pipeline solutions of vertical corner wire.

in an alternating fashion. This empowered the construction of the basic tQCA logic primitive called tQCA wire. The alternating propagation of state C effectively means that wires have to be of odd lengths [6].

While the straight wire can be constructed as a single stage pipeline (see Fig. 5a), the correct behavior of the corner wire is ensured by means of a pipeline of two stages, as can be seen on Fig. 5b. The first stage ensures the propagation of the input value to the corner, and the second stage ensures its propagation to the output cell.

One of the unique features of bQCA is coplanar rectangular wire crossover [18]. Unfortunately, in case of tQCA this is not possible as there is no equivalent to the rotated bQCA cell [2]. The only possible solution is the noncoplanar approach (using multiple layers of tQCA cells), at least until an alternative approach is found.

The vertical transmission of a cell's state can be achieved with the rearrangement of cells in a manner that one cell is placed above the other so that the minimum spacing h between quantum-dots remains unchanged (see Fig. 6a). Thus, both layouts, i.e., coplanar and noncoplanar, obey the same spacing rules, only the intercellular position is changed. With the described vertical tQCA cell placement one can construct a vertical tQCA wire that is used for the propagation of data between layers. The analysis of the behavior of the vertical wire (see Fig. 6b) during the transmission of states from input cell X to output cell Y shows that states propagate in alternating fashion, regardless of the input state. Comparing the behavior results in Fig. 4b and Fig. 6b indicates that the cell-cell Coulomb interaction and minimum energy condition differ between co-axial and co-planar arrangements in case of input states A and B, while remain the same in case of states C and D.

The promotion of states from a coplanar wire to a vertical wire, and vice versa, requires the presence of a tQCA that acts as a vertical corner wire, as presented in Fig. 7. Robust behavior can be achieved using the pipeline concept, i.e., splitting the corner wire to two stages, controlled by two phase shifted clock signals C_0 and C_1. The implementation itself is not so rigid as in the case of its coplanar counterpart (see Fig. 3b) and offers two possible approaches. The one demonstrated in Fig. 7a is directly derived from the coplanar solution, while the one showed in Fig. 7b uses clock signal C_0 for the control of the coplanar wire and signal C_1 for the control of the vertical wire.

The presented tQCAs facilitate the construction of a noncoplanar tQCA wire crossover. The two implementations of the vertical corner wire result in four possible solutions for the crossover, where two of them are shown in Fig. 8 and the other two are their combinations. For example, the crossover approach in Fig. 8a uses the pipeline solution based on corner wire shown in Fig. 7a for input and for output part. In order to avoid interference between the crossing wires two additional layers are needed, i.e., besides the main (bottom) layer. The middle layer is used only as a via layer, while the top one acts as the crossing wire. Hence, the crossing wires are separated by a distance of $2h$. The distance between the vertical wire and the wire that is crossed has to be at least $2r$.

Simulations show that the correct behavior of the crossover requires four pipeline stages controlled by four phase shifted clock signals C_0, C_1, C_2 and C_3, which determine a delay of one clock cycle. This means that the behavior of the crossover wire is independent of the clock phase applied to the crossed wire. It can be easily seen that the crossover wire can span across multiple wires on the bottom layer. The span depends only on the length of the crossing wire on the top layer.

IV. CONCLUSION

The interconnection crossover represents one of the most challenging design problems in the tQCA domain. This

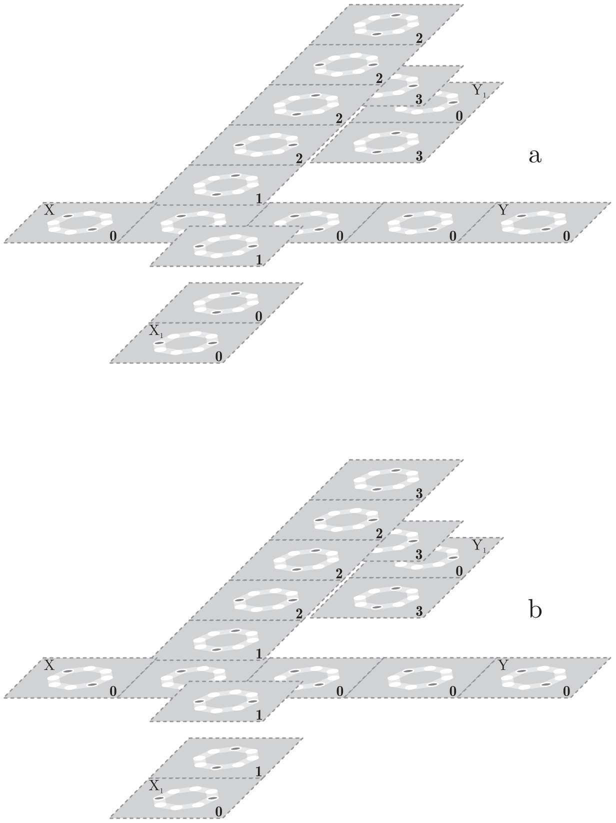


Figure 8. Two multilayer tQCA wire crossovers.

paper gives a solution that exploits a noncoplanar, i.e., multilayer, arrangement of tQCA cells with adiabatic pipeline control. The crossover constructed in this manner exhibits robustness and flexibility of data propagation. The latter goes on the account of using four pipeline stages, which on the other hand may introduce a synchronization problem, specially in the case of multiple crossovers of the same wire. Therefore, our research is focused on developing a crossover that would need less stages, thus diminishing data transfer delay. One of the most promising is a two-layer approach, which would also substantially simplify the fabrication challenges [20].

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