A novel comparator – a cryptographic design in quantum dot cellular automata

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Abstract: Ouantum-dot cellular automata (OCA). nanotechnology, is a branch of nano-electronics that attempts to create general computation at nano scale by controlling the position of electrons. The basic logic in QCA does not use voltage level for logic representation; rather it represents the binary state by polarisation of electrons in the quantum cell, which is basic building block of QCA. QCA technology has large potential to provide high space density, ultra-low power dissipation that enables us to build QCA circuits with faster speed, smaller size and high performance for integration and computation. QCA presents proficient solutions for several arithmetic circuits, such as adders, multipliers, comparators etc. This paper presents a thorough analysis of QCA-based universal FNZ gate (Khanday et al., 2013) with its stability proof upon which a new design of 1-bit comparator has been proposed. The proposed work uses novel implementation strategies, methodologies and new formulations of basic logic equations to make the proposed designs more efficient in terms of cell count, area, polarisation etc. The functionality of universal FNZ gate based 1-bit comparator has been tested by QCA designer where a comprehensive comparison with the formerly reported designs confirm the consistent performance and high efficiency of the proposed designs.

Keywords: nanotechnology; quantum-dot cellular automata; QCA; comparator; potential energy.

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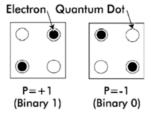
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1 Introduction

Quantum-dot cellular automata (QCA), a field of nanotechnology, recently been documented as one of the chief six incipient technologies with possible applications for imminent development of computers (Khanday et al., 2013; Wilson et al., 2002; Lent et al., 1993; Lent and Tougaw, 1997; Porod, 1997; Toth and Lent, 1999). Numerous studies have stated that QCA can be employed to design general-purpose data processing and memory circuits (Amlani et al., 2000; Walus et al., 2003; Vetteth et al., 2002; Frost et al., 2002). QCA has been proposed by Lent et al. at first, and verified analytically. QCA is estimated to realise high density, very high switching speed and exceptionally low power consumption.

QCA technology is established on the synergy of bi-stable QCA cells made from four quantum dots and is indicted with free electrons that are able to tunnel among adjacent dots. These electrons have a tendency to reside in antipodal sites because of their communal electrostatic repulsion. Therefore, there exist two corresponding actively minimal provisions of two electrons in a QCA cell, as revealed in Figure. 1. These two provisions are represented as cell polarisation P = +1 to represent logic '1' and P = -1 to represent logic '0'. By this, binary information of a QCA cell can thus be encoded in the charge configuration.

Figure 1 QCA cells showing binary information is encoded in two fully polarised diagonals of the cell



The polarisation of one cell sets the polarisation of a neighbouring cell by suitably arranging the QCA cells and it is then possible to implement entire combinational and sequential logic functions (Lent et al., 1993). As per former reports, a number of computing devices and logic gates (Berzon and Fountain, 1998) have already been implemented in QCA. There are a number of elementary applications that have been reported are the binary wire (Wilson et al., 2002), majority gate, AND gate (Lantz and Peskin, 2006), NOT gate (Lantz and Peskin, 2006), XOR gate (Lantz and Peskin, 2006), bit-serial adder (Tougaw and Lent, 1994; Wang et al., 2003), full adder (Lantz and Peskin, 2006; Tougaw and Lent, 1994; Fijany et al., 2003; Gin et al., 1999; Kim et al., 2007), multiplier (My and Mi, 2008), multiplexer

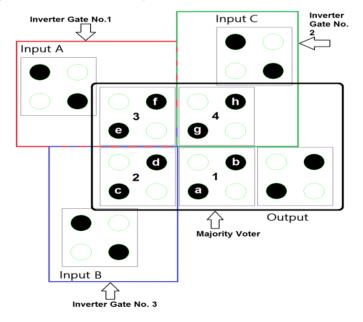
(Fijany et al., 2003; H"anninen and Taka, 2008), flip-flop (Vankamamidi et al., 2008b; Huang et al., 2007a; Momenzadeh et al., 2005), serial memory (Huang et al., 2007b; Vankamamidi et al., 2005b), parallel memory (Vankamamidi et al., 2008a), arithmetic logic unit (Fijany et al., 2003; Vankamamidi et al., 2005a), microprocessor (Vankamamidi et al., 2005a), programmable logic array (PLA) (Niemier et al., 2000), etc.

This paper comprises of the implementation of a novel universal FNZ gate based 1-bit comparator. In addition, the potential energy of the universal FNZ gate for all logic states has been calculated. Further, novel comparator design using Universal FNZ gate have also been compared with the earlier reported comparator designs.

2 Potential energy calculation

Universal FNZ gate comprises of three NOT gates located at input A, input B and input C with opposite outputs (as obvious) to that of the inputs as shown in Figure 2. Combining three NOT gates, outputs form a simple QCA wire. Thus, all the outputs of three NOT gates when combined have to follow the majority logic. For example, if the inputs to the universal FNZ gate are A=0, B=1 and C=0, their outputs will be 1, 0 and 1 respectively and hence, number of 1's as compared to the number of 0's are more. This means that the output of inverter input B will not remain in 0 state and hence change its state to 1 because of high columbic repulsion and potential energy. Similarly, when the inputs to the universal FNZ gate are A=1, B=1 and C=0, their outputs will be 0, 0 and 1 respectively and hence, number of 0's are more as compared to number of 1's. This means that the output of inverter input C will automatically change its state from 1 to 0 by following the majority logic.

Figure 2 Representation of the universal FNZ gate in terms of three inverters and majority voter (see online version for colours)



Thus, all the outputs of NOT gates will be either at 1 or 0 state depending upon the majority logic, columbic repulsion and potential energy. Therefore, the device cell (cell 1) in the universal FNZ gate follow the same state as that of the output of three NOT gates and consequently, the desired output is taken.

By calculating the electrostatic energy between each cell and its neighbouring cells, the energy of each state can be computed. Potential energy between electrons in a quantum dot cell i and one in cell j can be calculated from equation (1) where ε_0 is the permittivity of free space and ε_r is the relative permittivity of the quantum cell material. The potential energy between two quantum cellular automata (QCA) cells can be computed by rounding up over the entire dots in each cell given in equation (3).

$$U = \frac{1}{4\pi\varepsilon_0\varepsilon_r} \cdot \frac{Q_1Q_2}{\left|r_i - r_j\right|} \tag{1}$$

or

$$U = K \cdot \frac{Q_1 Q_2}{r}$$

where $K = 9 \times 10^{-9}$ and Q1 and Q2 are the charge of electron which is equal to $1.60217662 \times 10^{-19}$ C.

The potential energy between two electrons can be calculated from equation (1) and is represented as

$$U = \frac{23.04 \times 10^{-29}}{r} J \tag{2}$$

where 'U' is the potential energy and 'r' is the distance between two electrons.

$$U_T = \sum_{i=1}^n U_i \tag{3}$$

This electrostatic interaction is the main criteria to determine the kink energy between the two cells. Kink Energy between the two neighbouring cells is well-defined as the modification in the electrostatic energy between the two polarisation states. Thus, equations (4) and (5) represents the kink energy as

$$E_{\mathit{Kink}} = E_{\mathit{opposite polarisation}} - E_{\mathit{same polarisation}} \tag{4}$$

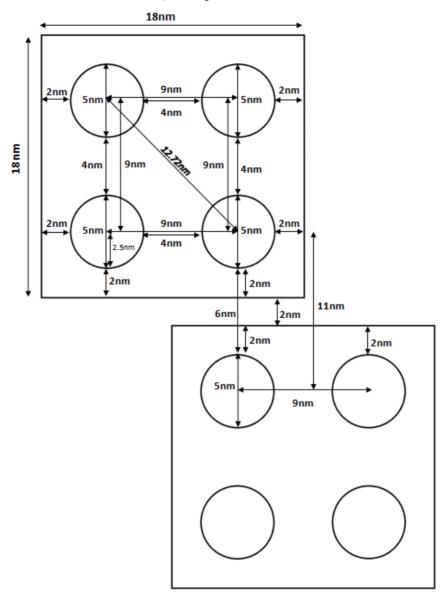
or

$$E_{Kink} = E_{inverting} - E_{non-inverting}$$
 (5)

Kink energy depends on the dimensions of QCA cells and the spaces between the cells but it does not be governed by the temperature at all.

In the environ of the QCA designer tool, complete QCA cell dimensions are defined to be 18×18 nm; the dot diameter is defined to be 5 nm and the inter-cell distance to be 2 nm. The Cell dimensions in QCA designer tool is shown in Figure 3, which are used to calculate the potential energy and kink energy are as follows:

Figure 3 Cell dimensions used in QCA designer tool



3 Calculation of potential energy for the complete stability of the universal FNZ gate logic with all its input combinations

Various logic states of the universal FNZ gate have been verified by calculating their potential energies and hence show the stable and robust performance in establishing various logic functions (shown in Table 1 to Table 8).

Table 1 When input A, B and C are at '-1' polarisation

					When inp	tts A, B and C t	When inputs A, B and C are at '-1' polarisation	risation			
		Quantum dot	Horizontal distance (nm)	Vertical distance (nm)	Total distance (nm)	Potential energy	Sum of potential energies	Total potential energy	Representation of logic states	Kink energy	Resultant output
Inverting	For cell 1	a & c	29	0	29	$7.94483 \mathrm{E}^{-21}$			Input C at '0'		
	and cell 2	a & d	20	6	21.9317122	$1.05053E^{-20}$	4 0001E-20		Input A at '0'		
		b & c	20	6	21.9317122	$1.05053E^{-20}$	4.9901E				
		р <i>%</i> ф	11	0	11	$2.09455E^{-20}$					
	For cell 1	a & e	29	20	35.22782991	$6.54028E^{-21}$			_ _ _ _ _ _		
	and cell 3	a & f	20	29	35.22782991	$6.54028E^{-21}$	3 33CBCE-20	1 220 TE-19			
		ь & e	20	11	22.82542442	$1.0094E^{-20}$	3.32080E	1.330/E			
		b & f	11	20	22.82542442	$1.0094E^{-20}$					
	For cell 1	a & g	6	20	21.9317122	$1.05053E^{-20}$			○•		
	and cell 4	a & h	0	29	29	$7.94483E^{-21}$	4 000111-20		•		
		b & g	0	11	111	$2.09455E^{-20}$	4.9901E		Input B at '0'		
		ь & h	20	6	21.9317122	$1.05053E^{-20}$				0 24455E-21	;
Non-inverting	For cell 1	a & c	20	0	20	$1.152E^{-20}$			Input C at '0'	- 0.24453E	-
	and cell 2	a & d	11	6	14.2126704	$1.62109E^{-20}$	4 693 97E-20		Input A at '0'		
		ь & c	29	6	30.3644529	$7.58782E^{-21}$	4.0030/E				
		b & d	20	0	20	$1.152E^{-20}$			9 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0		
	For cell 1	a & e	20	20	28.2827125	$8.14587E^{-21}$			000000000000000000000000000000000000000		
	and cell 3	a & f	11	29	31.01612484	$7.42839E^{-21}$	2 11485E-20 1 2482CE-19	1 2482 CE-19			
		b & e	29	11	31.01612484	$7.42839E^{-21}$	3.11483E	1.24820E			
		b & f	20	20	28.28427125	$8.14587E^{-21}$					
	For cell 1	a & g	0	20	20	$1.152E^{-20}$			○ ·		
	and cell 4	a & h	6	29	30.3644529	7.58782E- ²¹	4 783 875-20		•		
		b & g	6	11	14.2126704	$1.62109E^{-20}$	4.0030/E		Input B at '0'		
		b & h	0	20	20	$1.152E^{-20}$					

Notes: Therefore, non-inverting mode has lesser potential energy than inverting mode. Thus, the cell remains in its lower potential energy state and the desired output will be at logic '1' when all the inputs are at logic '0'. Therefore, non-inverting mode is the balance state for the output cell.

Table 2 When input A, B are at '-1' polarisation and C is at '+1'

	Resultant output												,1,	-											
	Kink energy												9 2445E-21	3.5 44 2.6											
sation	Representation of logic states	Input C at '1'	Input A at '0'			0			●	• •	Input 8 at 'O'			Input Cat '1'	Input A at '0'		•	0	• • • • • • • • • • • • • • • • • • •	• • •	•	• 0	Input B at 'O'		
s at '+l' poları	Total potential energy						1 2207E-19	1.330/1											2 11405E-20 1 24026E-19	1.24020E					Ī
sation and C i:	Sum of potential energies		4 9901E-20	1000			2 22COCE-20	3.32000E			4 0001E-20	4.9901E			4 68387E-20	4.0030/L			2 11405E-20	3.11463E			4 C0207E-20	4.0838/E	
e at '-1' polari	Potential energy	$7.94483E^{-21}$	$1.05053E^{-20}$	$1.05053\mathrm{E}^{-20}$	$2.09455E^{-20}$	$6.54028E^{-21}$	$6.54028E^{-21}$	$1.0094E^{-20}$	$1.0094E^{-20}$	$1.05053E^{-20}$	$7.94483E^{-21}$	$2.09455E^{-20}$	$1.05053E^{-20}$	$1.152E^{-20}$	$1.62109E^{-20}$	$7.58782E^{-21}$	$1.152E^{-20}$	$8.14587E^{-21}$	$7.42839E^{-21}$	$7.42839E^{-21}$	$8.14587E^{-21}$	$1.152E^{-20}$	$7.58782E^{-21}$	$1.62109E^{-20}$	$1.152E^{-20}$
When inputs A, B are at '-1' polarisation and C is at '+1' polarisation	Total distance (nm)	29	21.931712	21.931712	11	35.22783	35.22783	22.825424	22.825424	21.931712	29	11	21.931712	20	14.21267	30.364453	20	28.284271	31.016125	31.016125	28.284271	20	30.364453	14.21267	20
Wh	Vertical distance (nm)	0	6	6	0	20	29	11	20	20	29	11	6	0	6	6	0	20	29	11	20	20	29	11	20
	Horizontal distance (nm)	29	20	20	11	29	20	20	11	6	0	0	20	20	11	29	20	20	11	29	20	0	6	6	0
	Quantum dot	a & c	a & d	ь & c	b & d	а & е	a & f	b & e	b & f	a & g	a & h	b & g	b & h	а&с	a & d	b & c	р % d	а & е	a & f	ь & e	b & f	a & g	a & h	b & g	ь & h
		For cell 1	and cen z			For cell 1	and cell 3			For cell 1	and cell 4				and cell 2			For cell 1	and cell 3			For cell 1	and cell 4		
		Inverting												Non-inverting											

Notes: Therefore, non-inverting mode has lesser potential energy than inverting mode. Thus, the cell remains in its lower potential energy state and the desired output will be at logic '1' when two inputs are at logic '0' and one of the inputs at logic '1'. Therefore, non-inverting mode is the balance state for the output cell.

Table 3 When input A, C are at '-1' polarisation and B is at '+1' polarisation

Inverting For cell 1 and cell 2 For cell 1 and cell 3 and cell 3 and cell 3 and cell 1					•					
	Quantum dot	Horizontal distance (nm)	Vertical distance (nm)	Total distance (nm)	Potential energy (J)	Sum of potential energies (J)	Total potential energy (J)	Representation of logic states	Kink energy Resultant (J) output	esultant output
and cell 2 For cell 1 and cell 3 For cell 1	a & c	29	0	29	7.94483E ⁻²¹			Input C at '0'		
For cell 1 and cell 3 For cell 1 For cell 1 and cell 3 For cell 1 and cell 4	a&d	20	6	21.9317122	$1.05053E^{-20}$	4 0001 E-20		Input A at '0'		
For cell 1 and cell 3 For cell 1 For cell 1 For cell 1 and cell 4	b & c	20	6	21.9317122	$1.05053E^{-20}$	4.9901E				
Forcell 1 and cell 3 Forcell 1 and cell 4	b & d	11	0	11	$2.09455E^{-20}$			9 7 9		
and cell 3 For cell 1	a & e	29	20	35.22782991	$6.54028E^{-21}$			• • •		
For cell 1	a&f	20	29	35.22782991	$6.54028E^{-21}$	2 22CeCE-20	1 22020-19			
For cell 1 and cell 4	b & e	20	11	22.82542442	$1.0094E^{-20}$	3.32000E	1/0001			
For cell 1	b & f	11	20	22.82542442	$1.0094E^{-20}$			•		
and cell 4	a & g	6	20	21.9317122	$1.05053E^{-20}$			○●		
	t a&h	0	29	29	7.94483E ⁻²¹	4 0001 E-20		Input B at '1'		
	b & g	0	11	11	$2.09455E^{-20}$	4.9901E				
	b & h	20	6	21.9317122	$1.05053E^{-20}$				9 24455 E-21	;
Non-inverting For cell 1	a & c	20	0	20	$1.152E^{-20}$			Input C at '0'	- 8.24433E	-
and cell 2	a&d	11	6	14.2126704	$1.62109E^{-20}$	4 6000 TE-20		Input A at '0'		
	b & c	29	6	30.3644529	7.58782E ⁻²¹	4.0030/E				
	b & d	20	0	20	$1.152E^{-20}$					
For cell 1	a & e	20	20	28.28427125	$8.14587E^{-21}$			• •		
and cell 3	a&f	11	29	31.01612484	7.42839E ⁻²¹	2 1148 FE-20 1 2482 EE-19	1 24076E-19	• • • • • • • •		
	b & e	29	11	31.01612484	7.42839E ⁻²¹	3.11403E	1.24020E			
	b & f	20	20	28.28427125	$8.14587E^{-21}$					
For cell 1	a & g	0	20	20	$1.152E^{-20}$			0		
and cell 4	a&h	6	29	30.3644529	7.58782E ⁻²¹	4 6838 TE-20		Input 8 at '1'		
	b & g	6	11	14.2126704	$1.62109E^{-20}$	4.0030/E				
	b & h	0	20	20	$1.152E^{-20}$					

Notes: Therefore, non-inverting mode has lesser potential energy than inverting mode. Thus, the cell remains in its lower potential energy state and the desired output will be at logic '1' when two inputs are at logic '0' and one of the inputs at logic '1'. Therefore, non-inverting mode is the balance state for the output cell.

Table 4 When input A is at '-1' polarisation and B, C are at '+1' polarisation

			1.1	17			,				
		Quantum dot	Horizontal distance (nm)	verncal distance (nm)	Total distance (nm)	Potential energy (J)	Sum of potential energies (J)	Total potential energy (J)	Representation of logic states	Kink energy (J)	Resultant output
Inverting	For cell 1	а & с	20	0	20	$1.152\mathrm{E}^{-20}$			Input Cat '1'		
	and cell 2	a & d	29	6	30.3644529	7.58782E ⁻²¹	A 60307E-20		Input A at '0'		
		ь & c	11	6	14.2126704	$1.62109E^{-20}$	4.0030/E				
		b & d	20	0	20	$1.152E^{-20}$					
	For cell 1	a & e	20	20	28.28427125	$8.14587E^{-21}$					
	and cell 3	a & f	29	29	41.01219331	$5.61784E^{-21}$	3 730315-20	1 20200E-19			
		ь & e	11	11	15.55634919	$1.48107E^{-20}$	3.0/203E	1.30390E			
		b & f	20	20	28.28427125	$8.14587E^{-21}$					
	For cell 1	a & g	0	20	20	$1.152E^{-20}$) (
	and cell 4	a & h	6	29	30.3644529	$7.58782E^{-21}$	4 C0307E-20		Input B at '1'		
		b & g	6	11	14.2126704	$1.62109E^{-20}$					
		ь & h	0	20	20	$1.152E^{-20}$				2 67303E-21	6
Non-inverting	For cell 1	а&с	11	0	11	$2.09455E^{-20}$			Input C at 1'	-2.07202E	0
	and cell 2	a & d	20	6	21.9317122	$1.05053E^{-20}$	4 0001 E-20		Input A at 0'		
		ь & c	20	6	21.9317122	$1.05053E^{-20}$	4.9901E				
		b & d	29	0	29	$7.94483E^{-21}$					
	For cell 1	a & e	Ξ	20	22.82542442	$1.0094E^{-20}$			•		
	and cell 3	a & f	20	29	35.22782991	$6.54028E^{-21}$	3 2360CE-20	1 22 07E-19			
		ь & e	20	11	22.82542442	$1.0094E^{-20}$	3.32000E	1.330/E			
		b & f	29	20	35.22782991	$6.54028E^{-21}$					
	For cell 1	a & g	20	6	21.9317122	$1.05053E^{-20}$					
	and cell 4	a & h	0	29	29	$7.94483E^{-21}$	4 0001 E-20		Input B at 11		
		b & g	0	11	11	$2.09455E^{-20}$	4.9901E				
		b & h	6	20	21.9317122	$1.05053E^{-20}$					

Table 5 When input A is at '+1' polarisation and B, C are at '-1' polarisation

				211 11	n inpuis A is ai	+1 potarisatio	n ana inpuis D,	When inputs A is at $+1$ polarisation and inputs B, C are at -1 polarisation	risation		
		Quantum dot	Horizontal distance (nm)	Vertical distance (nm)	Total distance (nm)	Potential energy (J)	Sum of potential energies (J)	Total potential energy (J)	Representation of logic states	Kink energy (J)	Resultant output
Inverting	For cell 1	a & c	20	0	20	1.152E ⁻²⁰			finding C at ,O.		
	and cell 2	a & d	29	6	30.3644529	$7.58782E^{-21}$	4 C0207E-20		Imput A at '1'		
		ь & c	11	6	14.2126704	$1.62109E^{-20}$	4.0030/E				
		b & d	20	0	20	$1.152E^{-20}$					
	For cell 1	а & е	20	20	28.28427125	$8.14587E^{-21}$			•		
	and cell 3	a & f	29	29	41.01219331	$5.61784E^{-21}$	2 (2200711-20	1 20208E-19	0 0 0 0		
		b & e	11	11	15.55634919	$1.48107E^{-20}$	3.0/203E	1.30390E	0		
		b & f	20	20	28.28427125	$8.14587E^{-21}$			•		
	For cell 1	a & g	0	20	20	$1.152E^{-20}$			Input B at 'O'		
	and cell 4	a & h	6	29	30.3644529	$7.58782E^{-21}$	4 7626411-20				
		b & g	6	11	14.2126704	$1.62109E^{-20}$	4.6838/E				
		ь & h	0	20	20	$1.152E^{-20}$				2 673 03 12-21	;
Non-inverting	For cell 1	a & c	11	0	11	$2.09455E^{-20}$			Input C at '0'	2:0/202E	-
	and cell 2	a & d	20	6	21.9317122	$1.05053E^{-20}$	4 000111-20		Imput A at '1'		
		b & c	20	6	21.9317122	$1.05053E^{-20}$	4.9901E				
		b & d	29	0	29	$7.94483E^{-21}$			6 6		
	For cell 1	а & е	11	20	22.82542442	$1.0094E^{-20}$			•		
	and cell 3	a & f	20	29	35.22782991	$6.54028E^{-21}$, 22C0CE-20	1 2307E-19	2 0 0 0 0		
		b & e	20	11	22.82542442	$1.0094E^{-20}$	3.32000E	1.330/E	○ ● ○ ●		
		b & f	29	20	35.22782991	$6.54028E^{-21}$			·		
	For cell 1	a & g	20	6	21.9317122	$1.05053E^{-20}$			• 0		
	and cell 4	a & h	0	29	29	$7.94483E^{-21}$	4 000115-20		Input B at "O"		
		b & g	0	11	11	$2.09455E^{-20}$	4.9901E				
		b & h	6	20	21.9317122	$1.05053E^{-20}$					

Notes: Therefore, non-inverting mode has lesser potential energy than inverting mode. Thus, the cell remains in its lower potential energy state and the desired output will be at logic '1' when two inputs are at logic '0' and one of the inputs at logic '1'. Therefore, non-inverting is the balance state for the output cell.

Table 6 When input A, C are at '+1' polarisation and B is at '-1' polarisation

Proceeding Force a & c 2 0 0 0 0 0 0 0 0 0					Whe	en inputs A, C are	e at '+1' polaris	ation and input	When inputs A, C are at '+1' polarisation and input B is at '-1' polarisation	sation			
For cell a & c 20 0 20 1.152E ²⁰ a & d 29 9 9 30.3644529 7.88782E ²¹ b & d 20 0 20 1.152E ²⁰ a & d 20 0 20 2.82427125 8.14587E ²¹ b & d 20 2.82427125 8.14587E ²¹ a & d 20 2.9 30.3644529 7.88782E ²¹ b & d 20 20 2.82427125 8.14887E ²¹ a & d 20 20 2.82427125 1.30585E ²⁰ and cell a & d 20 20 2.9317122 1.05655E ²⁰ b & d 20 20 2.15278291 6.44887E ²¹ b & d 20 20 2.1537712 1.05655E ²⁰ b & d 20 20 2.1537712 1.05655E ²⁰ b & d 20 20 2.2278291 6.4091E ²⁰ b & d 20 20 2.2278291 6.4028E ²⁰ b & d 20 20 2.2278291 6.4028E ²⁰ b & d 20 20 2.3278291 6.4028E ²⁰ b & d 20 20 2.3278291 6.4028E ²⁰ b & d 0 0 0 0.0458E ²⁰ b & d 0 0 0 0.0458E ²⁰ b & d 0 0 0.0458E ²⁰ b			Quantum dot	Horizontal distance (nm)		Total distance (nm)	Potential energy (J)	Sum of potential energies (J)	Total potential energy (J)	Representation of l	logic states	Kink energy (J)	Resultant output
and cell 2 a & d 29 30.3644529 7.58782E ²³ 4.68387E ²³⁰ 4.68387E ²	Inverting	For cell 1	а & с	20	0	20	1.152E ⁻²⁰				Input C at '1'		
b & c 11 9 14.2126704 1.62109E ⁻²⁰ 1.3528 ⁻²⁰ 1.3528 ⁻²⁰ 1.30398E ⁻¹⁹ 2.0 2.0 2.0 2.828427125 3.67203E ⁻²⁰ 1.30398E ⁻¹⁹ 2.9 4.101219331 3.617845E ⁻²¹ 3.67203E ⁻²⁰ 1.30398E ⁻¹⁹ 3.67203E ⁻²⁰ 1.30398E ⁻¹⁹ 3.67203E ⁻²⁰ 1.30398E ⁻¹⁹ 3.67203E ⁻²⁰ 1.30398E ⁻¹⁹ 3.67203E ⁻²⁰ 1.3528 ⁻²⁰ 1.35288E ⁻²⁰ 1.35288E ⁻²⁰ 1.35288E ⁻²⁰ 1.35288E ⁻²⁰ 1.35278299 6.54028E ⁻²⁰ 1.35288E		and cell 2	a & d	29	6	30.3644529	$7.58782E^{-21}$	4 60307E-20		Input A at '1'	• (
For cell a & e 20 20 28.28427125 81.4587E ²³ 3.67203E ²³ 1.30398E ¹³ e & e 20 28.28427125 81.4587E ²³ 3.67203E ²³ 1.30398E ¹³ e & e 20 28.28427125 81.4587E ²³ 3.67203E ²³ 1.30398E ¹³ e & e 11 11 15.55634919 1.48107E ²³ 3.67203E ²³ e & e 20 20 20 20 20 20 20			ь & c	11	6	14.2126704	$1.62109E^{-20}$	4.0030/E		•	•		
For cell 1 a & e 20 20 28.28427125 8.14587E ⁻²¹ For cell 1 a & e 20 20 28.28427125 8.14587E ⁻²³ For cell 1 a & e 20 20 20 20 20 20 20 20 20 20 20 20 20			b & d	20	0	20	$1.152E^{-20}$			@ _ •	0,		
and cell 3 a & f = 29 = 29 41,0121931 5.61784E ²¹ 3.67203E ²⁹ 1.30398E ⁻¹⁹ 9.6 9.		For cell 1	а&е	20	20	28.28427125	$8.14587E^{-21}$			•	0		
Per cell a & b & c 11 11 15.55634919 1.48107E ⁻²⁰ 1.48107E ⁻²⁰ 1.152E ⁻²⁰ 1.152		and cell 3	a & f	29	29	41.01219331	$5.61784E^{-21}$	2 C7202E-20	1 20200E-19	္ စ	•		
For cell 1 a & g 0 20 28.28427125 8.14587E ⁻²¹ and cell 4 a & h 9 29 30.3644529 7.58782E ⁻²¹ 4.68387E ⁻²⁰ 4.6901E ⁻²⁰ 4.6901E ⁻²⁰ 4.9901E ⁻²⁰ 4.990			ь & e	111	11	15.55634919	$1.48107E^{-20}$	3.6/203E	1.30396E	•	•		
For cell 1 a & g 0 20 20 1.152E ²⁰ and cell 4 a & h 9 29 30.364459 7.58782E ²¹ 4.68387E ²⁰ hyperface of the cell 2 a & h 0 20 20 1.152E ²⁰ hyperface of the cell 3 a & h 0 20 20 1.152E ²⁰ hyperface of the cell 3 a & h 0 20 20 1.152E ²⁰ hyperface of the cell 4 a & h 0 1 1.42126704 1.62095E ²⁰ hyperface of the cell 3 a & h 0 20 2.9317122 1.05038E ²⁰ hyperface of the cell 4 a & h 0 20 2.9317122 1.05038E ²⁰ hyperface of the cell 4 a & h 0 20 2.282542442 1.0094E ²⁰ hyperface of the cell 4 a & h 0 20 2.9317122 1.05038E ²⁰ hyperface of the cell 4 a & h 0 20 2.9317122 1.05038E ²⁰ hyperface of the cell 4 a & h 0 20 2.9317122 1.05038E ²⁰ hyperface of the cell 4 a & h 0 20 2.9317122 1.05038E ²⁰ hyperface of the cell 4 a & h 0 20 2.9317122 1.05038E ²⁰ hyperface of the cell 4 a & h 0 20 2.9317122 1.05038E ²⁰ hyperface of the cell 4 a & h 0 20 2.9317122 1.05038E ²⁰ hyperface of the cell 4 a & h 0 20 2.9317122 1.05038E ²⁰ hyperface of the cell 4 a & h 0 20 2.9317122 1.05038E ²⁰ hyperface of the cell 4 a & h 0 20 2.9317122 1.05038E ²⁰ hyperface of the cell 4 a & h 0 20 2.9317122 1.05038E ²⁰ hyperface of the cell 4 a & h 0 0 20 2.9317122 1.05038E ²⁰ hyperface of the cell 4 a & h 0 0 0 0 0 0 0 0 0			b & f	20	20	28.28427125	$8.14587E^{-21}$			•			
and cell 4 a & h 9 29 30.3644529 7.58782E ⁻²¹ 4.68387E ⁻²⁰ hreat 8 at a 20 1.152E ⁻²⁰ and cell 2 a & c 11 0 1 1.152E ⁻²⁰ and cell 3 a & c 11 0 0 11 2.09455E ⁻²⁰ 1.05053E ⁻²⁰ 4.9901E ⁻²⁰ hreat 8 at a 20 9 21.9317122 1.05633E ⁻²⁰ 1.3307E ⁻¹⁹ hreat 8 at a 20 2.2.82542442 1.0094E ⁻²⁰ 3.32686E ⁻²⁰ 1.3307E ⁻¹⁹ hreat 8 at a 20 2.2.82542442 1.0094E ⁻²⁰ 3.32686E ⁻²⁰ 1.3307E ⁻¹⁹ hreat 8 at a 20 2.2.82542442 1.0094E ⁻²⁰ 3.32686E ⁻²⁰ 1.3307E ⁻¹⁹ hreat 8 at a 20 3.52782991 6.34028E ⁻²¹ hreat 8 at a 20 3.52782991 6.34028E ⁻²¹ hreat 8 at a 20 3.52782991 6.34028E ⁻²⁰ 1.05035E ⁻²⁰ hreat 8 at a 20 3.52782991 6.34028E ⁻²⁰ hreat 8 at a 3 at a 2 at a 3 at a		For cell 1	a & g	0	20	20	$1.152E^{-20}$			•			
b & g 9 11 14.2126704 1.62109E ⁻²⁰ 4.0838/E ⁻²¹ For cell 1 a & c 11 0 11 2.09455E ⁻²⁰ 4.9901E ⁻²⁰ 4.9901E ⁻²⁰ For cell 2 a & d 20 9 21.9317122 1.05053E ⁻²⁰ 4.9901E ⁻²⁰ 4.9901E ⁻²⁰ For cell 3 a & c 11 20 22.8254242 1.0094E ⁻²⁰ 3.3268GE ⁻²⁰ 1.3307E ⁻¹⁹ For cell 4 a & b 0 29 21.9317122 1.05053E ⁻²⁰ 3.3268GE ⁻²⁰ 1.3307E ⁻¹⁹ For cell 5 a & c 20 20 20 20 20 20 20		and cell 4	a & h	6	29	30.3644529	7.58782E ⁻²¹	4 7020411-20		Input B at '0'			
For cell 1 a & c 11 2.09458E ²⁰ and cell 2 a & d 1.152E ²⁰ 1.152E ²⁰ and cell 3 a & d 20 9 21.9317122 1.05053E ²⁰ 4.9901E ⁻²⁰ 1.3307E ⁻¹⁹ 1.05053E ⁻²⁰ and cell 3 a & d 20 9 21.9317122 1.05053E ⁻²⁰ 1.3307E ⁻¹⁹ 1.3307E ⁻¹⁹ 1.3307E ⁻¹⁹ 1.3307E ⁻¹⁹ 1.3307E ⁻¹⁹ 1.0094E ⁻²⁰ and cell 3 a & d 20 21.9317122 1.05053E ⁻²⁰ 1.3307E ⁻¹⁹ 1.3307E ⁻¹⁹ 1.3307E ⁻¹⁹ 1.3307E ⁻¹⁹ 1.05053E ⁻²⁰ and cell 4 a & b 0 29 2.1.9317122 1.05053E ⁻²⁰ 1.3307E ⁻¹⁹ 1.05053E ⁻²⁰ and cell 4 a & b 0 29 2.1.9317122 1.05053E ⁻²⁰ 1.3307E ⁻¹⁹ 1.05053E ⁻²⁰ 1			b & g	6	11	14.2126704	$1.62109E^{-20}$	4.6838/E					
For cell 1 a & c			ь & h	0	20	20	$1.152E^{-20}$					7 67707E-21	,0,
a & d 20 9 21.9317122 1.05053E ⁻²⁰ 4.9901E ⁻²⁰ 19901E ⁻²⁰	Non-inverting	For cell 1	a & c	11	0	11	$2.09455E^{-20}$				Input C at 'T'	-2.07/202E	>
b & c 20 9 21.9317122 1.05053E ⁻²⁰ + 7.270112 b & d 29 7.94483E ⁻²¹ + 7.370112 0 - 7.94483E ⁻²¹ a & e 11 20 22.82542442 1.0094E ⁻²⁰ 3.32686E ⁻²⁰ 1.3307E ⁻¹⁹ b & e 20 11 22.82542442 1.0094E ⁻²⁰ 3.32686E ⁻²⁰ 1.3307E ⁻¹⁹ b & f 20 21 22.82542442 1.0094E ⁻²⁰ 3.32686E ⁻²⁰ 1.3307E ⁻¹⁹ a & g 20 11 22.82542442 1.0094E ⁻²⁰ 4.9901E ⁻²⁰ 1.3307E ⁻¹⁹ a & g 20 21.9317122 1.05633E ⁻²⁰ 4.9901E ⁻²⁰ 4.9901E ⁻²⁰ b & g 0 11 2.09455E ⁻²⁰ 4.9901E ⁻²⁰ 4.9901E ⁻²⁰		and cell 2	a & d	20	6	21.9317122	$1.05053E^{-20}$	4 0001E-20		Input A at '1'	•		
b & d 29 7.94483E ⁻²¹ 9.0483E ⁻²⁰ a & e 11 20 22.8254242 1.0094E ⁻²⁰ 6.54028E ⁻²¹ a & f 20 29 35.22782991 6.54028E ⁻²¹ 3.32686E ⁻²⁰ 1.3307E ⁻¹⁹ b & e 20 11 22.8254242 1.0094E ⁻²⁰ 3.32686E ⁻²⁰ 1.3307E ⁻¹⁹ a & f 29 21.9317122 1.05053E ⁻²⁰ 4.9901E ⁻²⁰ 1.3307E ⁻¹⁹ a & b 0 29 21.94483E ⁻²¹ 4.9901E ⁻²⁰ 1.9901E ⁻²⁰ b & g 0 11 1 2.09455E ⁻²⁰ 4.9901E ⁻²⁰ b & b 0 20 21.9317122 1.05053E ⁻²⁰ 4.9901E ⁻²⁰			ь & c	20	6	21.9317122	$1.05053E^{-20}$	4.9901E		•	•		
a & e 11 20 22.82542442 1.0094E ⁻²⁰ a & f 20 29 35.22782991 6.54028E ⁻²¹ 3.3268GE ⁻²⁰ 1.3307E ⁻¹⁹ 0 b & e 20 11 22.82542442 1.0094E ⁻²⁰ 3.3268GE ⁻²⁰ 1.3307E ⁻¹⁹ 0 a & g 20 11 22.8254242 1.0094E ⁻²⁰ 4.9901E ⁻²⁰ 1.3307E ⁻¹⁹ a & g 20 21.9317122 1.05053E ⁻²⁰ 4.9901E ⁻²⁰ 4.9901E ⁻²⁰ 1.090488 at W b & g 0 11 2.09455E ⁻²⁰ 4.9901E ⁻²⁰ 1.05053E ⁻²⁰			b & d	29	0	29	$7.94483E^{-21}$			• • •			
a & f 20 35.22782991 6.54028E ⁻²¹ 3.3268GE ⁻²⁰ 1.3307E ⁻¹⁹ 0 b & e 20 11 22.8254242 1.0094E ⁻²⁰ 3.3268GE ⁻²⁰ 1.3307E ⁻¹⁹ a & f 29 20 35.22782991 6.54028E ⁻²¹ 4.9901E ⁻²⁰ a & b 0 29 21.9317122 1.05053E ⁻²⁰ 4.9901E ⁻²⁰ b & g 0 11 11 2.09455E ⁻²⁰ 4.9901E ⁻²⁰ b & b 0 20 21.9317122 1.05053E ⁻²⁰ 4.9901E ⁻²⁰		For cell 1	а & е	11	20	22.82542442	$1.0094E^{-20}$			•	0		
b & c 20 11 22.8254242 1.0094E ⁻²⁰ 5.32000E 1.3307E 2 1 2 2 2 2 2 3 2 2 2 2		and cell 3	a & f	20	29	35.22782991	$6.54028E^{-21}$	2 22 COCE-20	1 2207E-19	0	•		
b&f 29 20 35.22782991 6.54028E ⁻²¹ a&g 20 9 21.9317122 1.05053E ⁻²⁰ a&h 0 29 29 7.94483E ⁻²¹ b&g 0 11 11 2.09455E ⁻²⁰ b&h 9 20 21.9317122 1.05053E ⁻²⁰			ь & e	20	11	22.82542442	$1.0094E^{-20}$	3.32000E	1.330/E	200	8		
a & g 20 9 21.9317122 1.05053E ²⁰ a & h 0 29 29 7.94483E ²¹ 4.9901E ⁻²⁰ b & g 0 11 11 2.09455E ²⁰ 4.9901E ⁻²⁰ b & h 9 20 21.9317122 1.05053E ⁻²⁰			b & f	29	20	35.22782991	$6.54028E^{-21}$			0 6)		
a&h 0 29 29 7.94483E ⁻²¹ b&h 0 11 11 2.09455E ⁻²⁰ b&h 9 20 21.9317122 1.05053E ⁻²⁰		For cell 1	a&g	20	6	21.9317122	$1.05053E^{-20}$			9 (
0 11 11 $2.09455E^{-30}$ $7.5701L$ 9 20 21.9317122 $1.05053E^{-30}$		and cell 4	a & h	0	29	29	$7.94483E^{-21}$	4 0001E-20		(A) 40 H			
9 20 21.9317122			b & g	0	11	11	$2.09455E^{-20}$	4.2501E					
			b & h	6	20	21.9317122	$1.05053E^{-20}$						

Notes: Therefore, inverting mode has lesser potential energy than non-inverting mode. Thus, the cell remains in its lower potential energy state and the desired output will be at logic '0' when two inputs are at logic '1' and one of the inputs at logic '0'. Therefore, inverting mode is the balance state for the output cell.

Table 7 When input A, B are at '+1' polarisation and C is at '-1' polarisation

								*	r,		
		Quantum dot	Horizontal distance (nm)	Vertical distance (nm)	Total distance (nm)	Potential energy (J)	Sum of potential energies (J)	Total potential energy (J)	Representation of logic states	Kink energy (J)	Resultant output
Inverting	For cell 1	a & c	20	0	20	$1.152E^{-20}$			Input C at '0'		
	and cell 2	a & d	29	6	30.3644529	7.58782E ⁻²¹	4 C0207E-20		Input A at '1'		
		ь & c	11	6	14.2126704	$1.62109E^{-20}$	4.0838/E		•		
		р <i>&</i> d	20	0	20	$1.152E^{-20}$			● · · · · · · · · · · · · · · · · · · ·		
	For cell 1	a & e	20	20	28.28427125	$8.14587E^{-21}$			•		
	and cell 3	a & f	29	29	41.01219331	$5.61784E^{-21}$	2 672001-20	1 20200E-19	• • • • • •		
		ь & e	11	11	15.55634919	$1.48107E^{-20}$	3.0/203E	1.30396E			
		b & f	20	20	28.28427125	$8.14587E^{-21}$			•		
	For cell 1	a & g	0	20	20	$1.152E^{-20}$			•		
	and cell 4	a & h	6	29	30.3644529	7.58782E ⁻²¹	4 C0207E-20		Input 8 at '1'		
		b & g	6	11	14.2126704	$1.62109E^{-20}$	4.0030/E				
		ь & h	0	20	20	$1.152E^{-20}$				7 67787E-21	,0,
Non-inverting		а&с	11	0	11	$2.09455E^{-20}$			Input C at '0'	-2.07/202E	>
	and cell 2	a & d	20	6	21.9317122	$1.05053E^{-20}$	4 000115-20		Input A at '1'		
		b & c	20	6	21.9317122	$1.05053E^{-20}$	4.9901E		•		
		b & d	29	0	29	$7.94483E^{-21}$			् • •		
	For cell 1	a & e	11	20	22.82542442	$1.0094E^{-20}$			•		
	and cell 3	a & f	20	29	35.22782991	$6.54028E^{-21}$	3 33686E-20	1 2207E-19			
		ь & e	20	11	22.82542442	$1.0094E^{-20}$	3.32080E	1.330/E	2 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	*	
		b & f	29	20	35.22782991	$6.54028E^{-21}$					
	For cell 1	a & g	20	6	21.9317122	$1.05053E^{-20}$					
	and cell 4	a & h	0	29	29	$7.94483E^{-21}$	4 0001E-20		lorurt & as "1"		
		b & g	0	11	11	$2.09455E^{-20}$	4.9901E		w random		
		b & h	6	20	21.9317122	$1.05053E^{-20}$					

Notes: Therefore, inverting mode has lesser potential energy than non-inverting mode. Thus, the cell remains in its lower potential energy state and the desired output will be at logic '0' when two inputs are at logic '1' and one of the inputs at logic '0'. Therefore, inverting mode is the balance state for the output cell.

Table 8 When input A, B and C are at '+1' polarisation

					When	inputs A, B and	When inputs A, B and C are at '+1' polarisation	olarisation			
		Quantum dot	Horizontal distance (nm)	Vertical distance (nm)	Total distance (nm)	Potential energy (J)	Sum of potential energies (J)	Total potential energy (J)	Representation of logic states	S Kink energy (J)	Resultant output
Inverting	For cell 1	а & с	20	0	20	$1.152E^{-20}$			input C at '1'		
	and cell 2	a & d	29	6	30.3644529	7.58782E ⁻²¹	4 69397E-20		Input A at '1'		
		ь & c	11	6	14.2126704	$1.62109E^{-20}$	4.0030/E		•		
		b & d	20	0	20	$1.152E^{-20}$			् • •		
	For cell 1	a & e	20	20	28.28427125	$8.14587E^{-21}$			•		
	and cell 3	a & f	29	29	41.01219331	$5.61784E^{-21}$	3 67303E-20	1 20200E-19	့ ဓ ့ ဓ	- 2	
		ь & e	11	11	15.55634919	$1.48107E^{-20}$	3.6/203E	1.30396E	• • • • • • • • • • • • • • • • • • •		
		b & f	20	20	28.28427125	$8.14587E^{-21}$			•		
	For cell 1	a & g	0	20	20	$1.152E^{-20}$			•		
	and cell 4	a & h	6	29	30.3644529	7.58782E ⁻²¹	4 60307E-20		Input 8 at '1'		
		b & g	6	11	14.2126704	$1.62109E^{-20}$	4.0038/E				
		b & h	0	20	20	$1.152E^{-20}$				2 67387E-21	,0,
Non-inverting	For cell 1	а & с	11	0	11	$2.09455E^{-20}$			Input C at '1.	-2.01282E	
	and cell 2	a & d	20	6	21.9317122	$1.05053E^{-20}$	4 0001E-20		Input A at '1'		
		b & c	20	6	21.9317122	$1.05053E^{-20}$	4.9901E		•		
		b & d	29	0	29	$7.94483E^{-21}$			ୁ ଜ ୁ ତ		
	For cell 1	a & e	11	20	22.82542442	$1.0094E^{-20}$			•		
	and cell 3	a & f	20	29	35.22782991	$6.54028E^{-21}$	7 23 CBCE-20	1 2 2 0 7 E-19	• • • •		
		ь & e	20	11	22.82542442	$1.0094E^{-20}$	3.32080E	1.330/E	• • • •	5	
		b & f	29	20	35.22782991	$6.54028E^{-21}$			•		
	For cell 1	a & g	20	6	21.9317122	$1.05053E^{-20}$			•		
	and cell 4	a & h	0	29	29	$7.94483E^{-21}$	4 0001E-20		Input 8 at '1"		
		b & g	0	11	11	$2.09455E^{-20}$	4.9301E				
		b & h	6	20	21.9317122	$1.05053E^{-20}$					

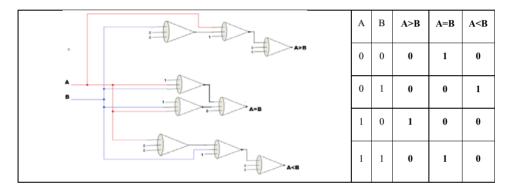
Notes: Therefore, inverting mode has lesser potential energy than non-inverting mode. Thus, the cell remains in its lower potential energy state and the desired output will be at logic '0' when two inputs are at logic '1' and one of the inputs at logic '0'. Therefore, inverting mode is the balance state for the output cell.

4 Proposed work

4.1 Universal FNZ gate based 1-bit comparator

A commonly suitable combinational logic circuit is the digital comparator. Binary or digital comparators are built from typical AND, NOR and NOT gates that associates the digital signals existing at their input extremes and assembles an output subject to the condition of those inputs. A digital comparator, also called as magnitude comparator, is a hardware electronic device that apprehends two numbers as input in binary form and decides whether one number is greater than, less than or equal to the other number. Figure 4 shows the block diagram of 1-bit comparator by means of the universal FNZ gate.

Figure 4 Block diagram of 1-bit comparator using universal FNZ gate and its truth table (see online version for colours)



The universal FNZ gate based 1-bit binary comparator obtains two bits 'A' and 'B' as inputs and determines the result whether they are equal, less or greater than each other. These possible states are signified via three output signals, called as A=B, A>B, B>A when A = B, A>B and B>A respectively.

In the first section, the universal FNZ gate based A > B function has been implemented in QCA. It comprises of 12 QCA cells and having 12,496.00 nm² = 0.01 um² area. The QCA implementation of A>B function is shown in Figure 5 and its simulation results are given in Figure 6.

Figure 5 QCA implementation of Universal FNZ gate based A>B logic function (see online version for colours)

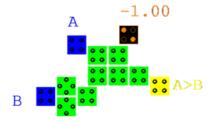
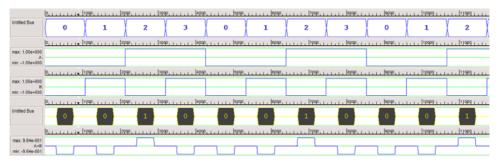


Figure 6 Simulation result of universal FNZ gate based A>B function (see online version for colours)



In the second section, the Universal FNZ gate based B > A function has been implemented in QCA. It comprises of 12 QCA cells and having 12496.00 nm² = 0.01 um² area same as that of A > B logic function. The QCA implementation of B > A function is shown in Figure 7 and its simulation results are given in Figure 8.

Figure 7 QCA implementation of the Universal FNZ gate based B>A logic function (see online version for colours)

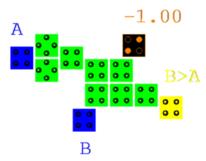
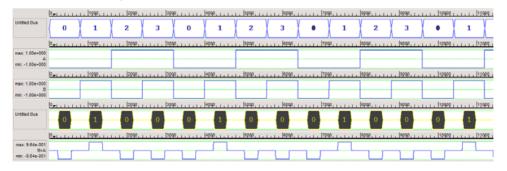


Figure 8 Simulation result of the universal FNZ gate based B>A function (see online version for colours)



In the last section, the universal FNZ gate based A = B function has also been implemented in QCA. It comprises of 48 cells and is having 42864.00 nm² = 0.04 um² of area. The QCA implementation of A = B function is shown in Figure 9 and its simulation results are given in Figure 10.

Figure 9 QCA implementation of the universal FNZ gate based A = B logic function (see online version for colours)

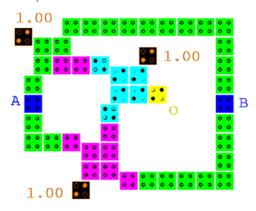


Figure 10 Simulation result of the universal FNZ gate based A = B function (see online version for colours)

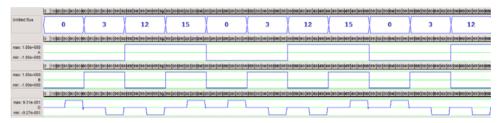


Figure 11 QCA implementation of the universal FNZ gate based 1-bit comparator (see online version for colours)

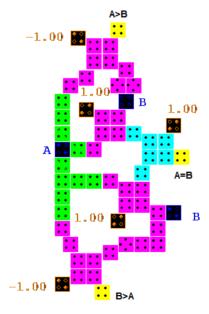


Figure 12 Simulation result of the universal FNZ gate 1-bit comparator (see online version for colours)

Table 9 Comparison table of previous reported 1-bit comparator with proposed 1-bit comparator

Parameters	1-bit comparator (Ke-ming and Yin-shui, 2007)	1-bit comparator (Ghosh et al., 2012)	1-bit comparator (Abdullah-Al-Shafi and Bahar, 2016)	Proposed 1-bit comparator
No. of cells	100	73	117	58
Area (µm²)	0.13	0.06	0.182	0.055
Input to output delay	Four clock zone	Four clock zone	Two clock zone	Three clock zone

Finally, a new design approach of 1-bit binary comparator using Universal FNZ Gate has been implemented in QCA. The proposed work employs novel implementation approaches, procedures and new formulations of elementary logic equations which marks the comparison function applied to the comparator more effective. The proposed universal FNZ gate based 1-bit comparator comprises only 58 cells and area 55,680.00 nm² = 0.055 um² which is much less as compared to the previously reported designs shown in Table 9. The design uses less clock cycles and has good polarisation that makes it much fault tolerant design. The implementation of Universal FNZ Gate based 1-bit comparator in QCA is shown in Figure 11 and its simulation result are given in Figure 12.

In Semiconductor QCA, composite hetero-structures of Gallium Arsenide (GaAs) are employed to produce quantum dots that are capable to trap electrons. For practical use, the operating temperature is always very low but higher than metal-dot QCA. So, in order to increase the operating temperature, cell sizes need to be reduced at some nanometres which is not possible in existing technology. In addition to this, in realising complex QCA structures, the effect of defect rate due to the fabrication process can make the QCA construction inoperable with the limitation in its practical implementation. One more thing, practical implementation has not been initiated in QCA yet. Till now, it is on the theoretical means not on fabrication means which is an undertaking in several laboratories using number of approaches, still it will be our future work to do the practical implementation of QCA circuits

5 Conclusions

This paper comprises of a novel universal FNZ Gate that has been introduced in a highly stable manner. 1-bit comparator has been designed in order to make QCA implementation more reliable, efficient, and robust and fault tolerant. The design utilises lesser number of clock phases, less area, less number of cells and has significantly smaller wire length, which leads to kink-free operation at higher operating temperature. The functionality of universal FNZ gate based 1-bit comparator has been verified by QCA designer tool where comprehensive comparisons with the earlier stated designs confirm the consistent performance of the proposed designs. Further, to upsurge the robustness of the QCA design, various design concerns have also been addressed.

6 Future scope

There are a number of issues which need to be addressed in the near future, such as technology issues (actual implementation of clocking zones, specific methods, tools and design rules need to be developed), fabrication issues (a great challenge and a long range undertaking), designing automation tools (in order to increase the user-friendliness of QCA designer) that will apply to all the potential QCA structures with immediate benefits and clearer architectural goals with a benchmark for nanofabrication methods.

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