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SINGLE-ELECTRON SEQUENTIAL NANOCIRCUITS AND THEIR MODELS

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Abstract**—***Memorizing nanodrives are distinguished by a large variety of majority trigger structures, which are the basic fragments of the the nanocircuit of a high integration level. The paper describes the synthesis of reliable sequential nanodevices of single- electronics based on the technology of quantum cellular automata. When constructing majority nano-circuits with memory, the theory of finite automata is used. The order of computer design of different types of arithmetic and logic nanodevices is analyzed. High-speed parallel-acting and paraphase control nanoregisters control are created.*

Index Terms—Quantum automata; majority logic; single-electonics; nanoregisters; computer design; models.

I. INTRODUCTION

The concept of a finite automaton arose in the middle of the 20th century in connection with attempts to mathematically describe the functioning of nervous systems, computing machines and other technical automata [1]. A characteristic feature of this class of mathematical models is the finiteness (and, therefore, the discreteness) of the sets of elements that make up the mathematical model. Further development of the theory proceeded by considering infinite automata of one or another type, introducing non-deterministic relations (random functions) between the input and output of the automaton [2], etc.

II. SYNTHESIS OF BASIC NANOTRIGGERS

Let's consider the basic principles of construction and operation of the most common trigger nanoelements [3].

A trigger is a device capable of forming two constant values of the output signal and changing these values in a jerky manner under the influence of an external control signal. In the general case, the flip-flop contains the memory element itself and some input combinational circuit that converts the input signals of the flip-flop into the signals needed to control the memory element.

Existing types of triggers can be classified according to different features. Most often, triggers are classified by the type of informational (instructive) inputs used. The following types of basic information inputs of the trigger are distinguished:

- R is the separate flip-flop reset input ($Q = 0$);
- S is the separate trigger setup input ($Q = 1$);
- K is the universal trigger reset input ($Q = 0$);
- J is the universal trigger installation input ($Q = 1$);
- T is the arithmetic input of the trigger;
- D is the informational input of the flip-flop switch to the state corresponding to the logic level on this input;
- C is the synchronizing or control input.

Thus, the definition of "synchronous RS flip-flop with inverse static inputs" means that the flip-flop in question has three information inputs: the set input S, the reset input R and the sync input C; switching of the trigger occurs at moments of time due to the appearance of an active logic signal at the synchronization input C = 0, and to switch to the inputs R or S, a low logic level must be applied, i.e., a low signal 0 (R = 0 or S = 0). Such inputs are denoted by C, R and S, respectively.

When synthesizing majority nanotriggers, in order to save equipment, it is advisable to use majority elements (ME) as an elementary automaton, which combines logic functions with delay functions [4]. The ME transition matrix as a delay element has the following form:

$$\begin{array}{r|c|} & q \\ 0-0 & 0 \\ 0-1 & 1 \\ 1-0 & 0 \\ 1-1 & 1 \end{array}$$

where the types of transitions are written to the left of the matrix.

Consider the procedure for building basic nanotriggers with different numbers of inputs.

A split-input flip-flop (RS flip-flop) has an input S = x_1 to set to a “1” state and an input R = x_0 to set to a “0” state. The functions of transitions and excitation of the trigger with separate inputs are given in the Table I [5]. It corresponds to the analytical form of the species record:

$$q\left(t_{i+1}\right) = \bar{R}(t_i)q(t_i) \vee S(t_i).$$

TABLE I. FUNCTIONS OF TRANSITIONS AND EXCITATION OF THE RS-TRIGGER

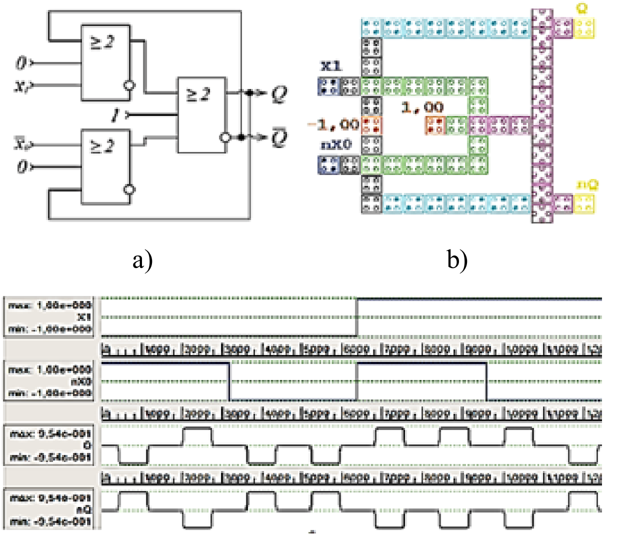
x_1	x_0	Q_1	Q_{t+1}	q
0	0	0	0	0
0	0	1	1	1
0	1	0	0	0
0	1	1	0	0
1	0	0	1	1
1	0	1	1	1
1'	1'	0	–	a_1
1'	1'	1	–	a_2

In the case of prohibited combinations of input signals, noted in the Table I units with dashes 1', function excitation can take an arbitrary value (a_1, a_2). Depending on the specific values of the undetermined coefficients a_1 and a_2, it is possible to synthesize several variants of flip-flop nanocircuits with separate inputs.

Option 1. $a_1 = 1$, $a_2 = 0$:

$$q = \bar{x}_1\bar{x}_0Q_t \vee x_1\bar{x}_0\bar{Q}_t \vee x_1\bar{x}_0Q_t = x_1\bar{Q}_t \vee \bar{x}_0Q_t,$$
$$q = \mathrm{maj}\left(\mathrm{maj}\left(x_1,\bar{Q}_t,0\right),\ \mathrm{maj}\left(\bar{x}_0,Q_t,0\right),1\right).$$

The structural diagram of a single-electron flip-flop with separate inputs, constructed according to previous equation, and the simulation results are shown in Fig. 1.



a) b)

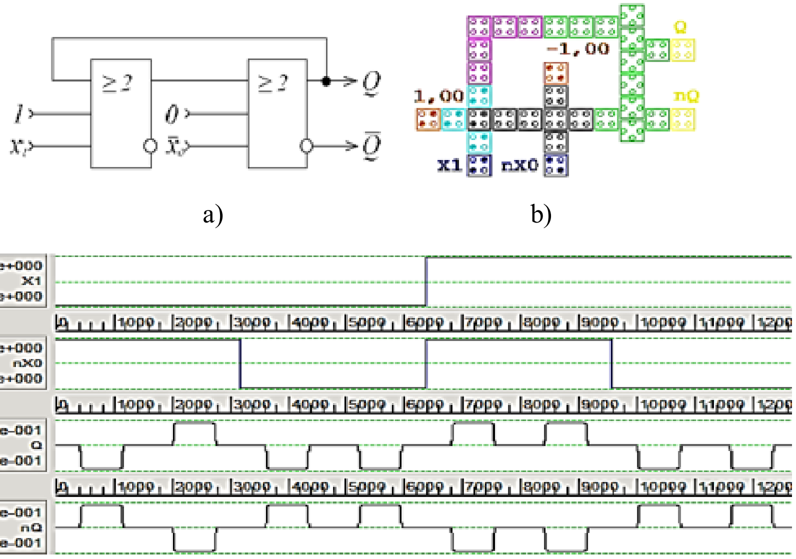
c)

Fig. 1. RS trigger (modification 1): (a) is the structural diagram; (b) is the nanocircuit on quantum automata [1]; (c) is the results of modeling the signals of the logic states of the RS-trigger in CAD QCADesigner [6]

Option 2. $a_1 = a_2 = 1$:

$$q = \bar{x}_1\bar{x}_0Q_t \vee x_1\bar{x}_0\bar{Q}_t \vee x_1\bar{x}_0Q_t = \bar{x}_0(x_1 \vee Q_t),$$
$$q = \mathrm{maj}\left(\mathrm{maj}\left(x_1,Q_t,1\right),\bar{x}_0,0\right).$$

The second version of the trigger scheme with separate inputs is shown in Fig. 2.



a) b)

c)

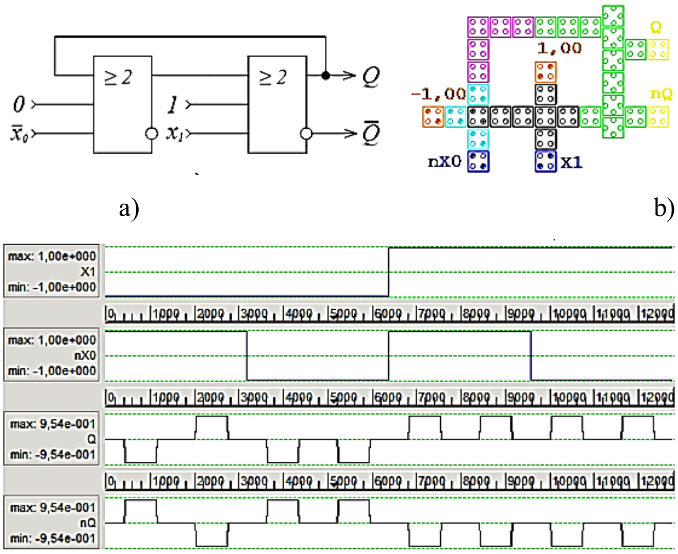
Fig. 2. RS trigger (modification 2): (a) is the structural diagram; (b) is the nanocircuit on quantum automata; (c) is the results of modeling the signals of the logic states of the RS-trigger in CAD QCADesigner

Option 3. $a_1 = a_2 = 0$:

$$q = \bar{x}_1\bar{x}_0 Q_t \vee x_1\bar{x}_0\bar{Q}_t \vee x_1\bar{x}_0 Q_t \vee x_1\bar{x}_0 Q_t = x_1 \vee \bar{x}_0 Q_t,$$

$$q = \mathrm{maj}\big(\mathrm{maj}(\bar{x}_0, Q_t, 0), x_1, 1\big).$$

The third version of the trigger circuit with separate inputs is shown in Fig. 3.



a) b)

c)

Fig. 3. RS trigger (modification 3): (a) is the structural diagram; (b) is the nanocircuit on quantum automata; (c) is the results of modeling signals of logic states in CAD CADesigner

Option 4. $a_1 = 0$, $a_2 = 1$:

$$\begin{aligned} q &= \bar{x}_1\bar{x}_0 Q_t \vee x_1\bar{x}_0\bar{Q}_t \vee x_1\bar{x}_0 Q_t \vee x_1 x_0 Q_t \\ &= x_1\bar{x}_0 \vee \bar{x}_0 Q_t \vee x_1 Q_t, \end{aligned}$$

$$f_{x_1 x_0} = \bar{x}_1 Q_t \vee x_1 Q_t = Q_t,$$

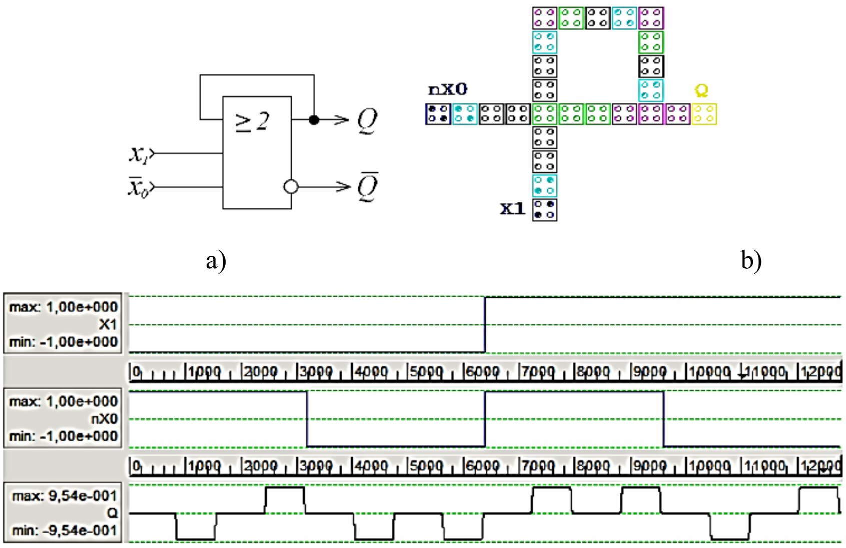
$$f_{x_1 \bar{x}_0} = x_1 \vee x_1 Q_t = x_1,$$

$$\begin{aligned} q &= \mathrm{maj}\big(\mathrm{maj}(x_1, x_0, x_1), \mathrm{maj}(\bar{x}_1, \bar{x}_0, x_1) Q_t\big) \\ &= \mathrm{maj}(x_1, x_0, Q_t). \end{aligned}$$

The circuit of the trigger with separate inputs, constructed in accordance with previous equation, is shown in Fig. 4.

Thus, all four modifications of RS nanotriggers on quantum MEs have the same time characteristics.

The last version of the RS-trigger (Fig. 4) is the most optimal and is implemented only on one universal ME (UME) without using a constant voltage level.



a) b)

c)

Fig. 4. RS trigger (modification 4): (a) is the structural diagram; (b) is the nanocircuit on quantum automata; (c) is the results of modeling signals of logic states in CAD QCADesigner

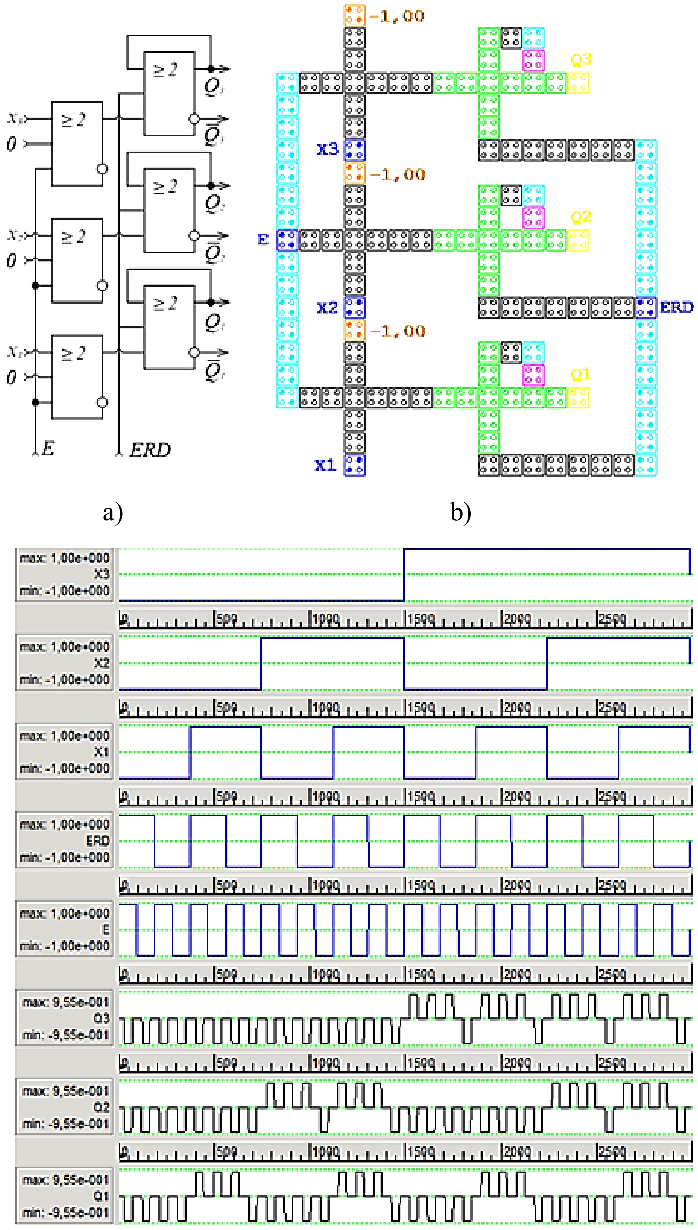
We will use RS flip-flops with separate inputs to design one-electron parallel nanoregisters. The transition matrix of such triggers looks like this:

			q_0
0	–	0	0
0	–	1	X
1	–	0	X
1	–	1	1

where X is the signal that was at the output of the trigger at the previous moment in time [7].

The nanoregister of parallel action without shift chains is designed to receive and store the parallel code of a number and is a set of the simplest RS flip-flops with separate inputs (Fig. 5 a and b).

The total number of quantum cellular automata of the register nanocircuit is 129. Dimensions of quantum cellular automata: (18×18) nm. The distance between the centers of quantum cellular automata is 20 nm. The diameters of the quantum islands are 5 nm. The overall dimensions of the register of parallel action are: (340 × 420) nm.



a) b)

c)

Fig. 5. Parallel register with single input control: (a) is the structural diagram; (b) is the nanocircuit on quantum automata; (c) is the results of simulation of logic state signals in CAD QCADesigner

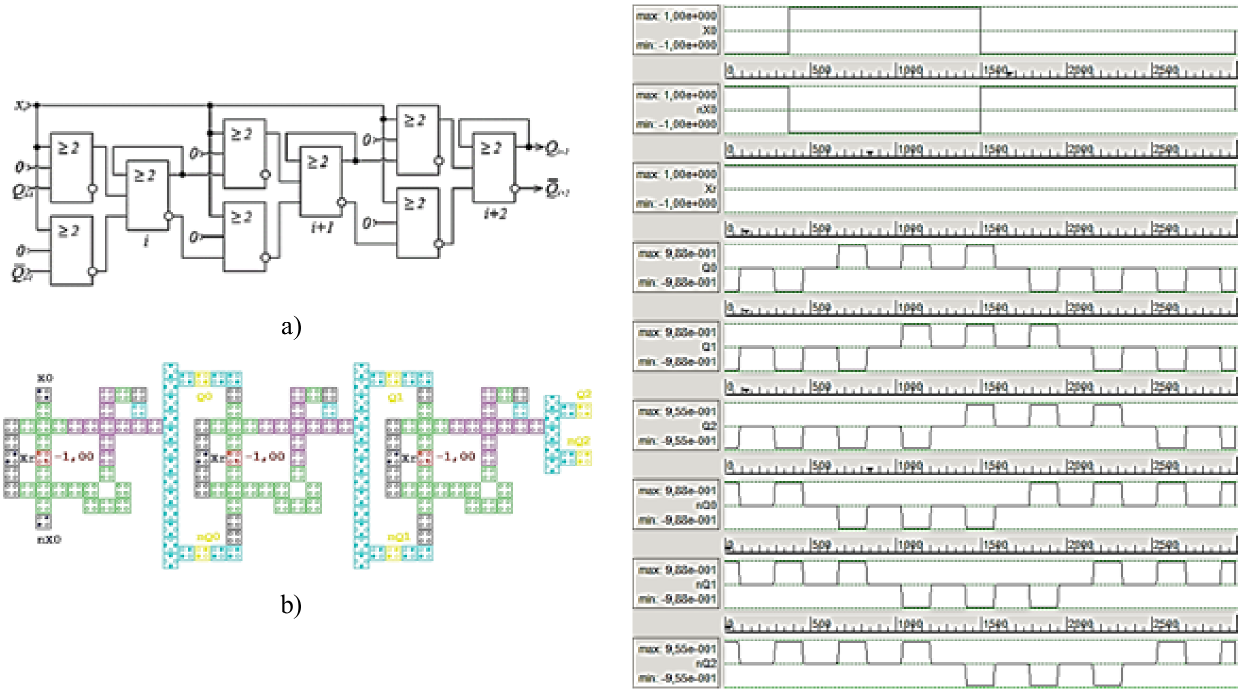
Figure 6 shows a register with a shift towards higher digits. When synthesizing shift registers as an elementary automaton, a flip-flop with separate inputs is usually used, the transition matrix of which has the form:

$$\begin{array}{ccc||cc||} & & & q_0 & q_1 \\ \hline 0 & - & 0 & a_1 & 0 \\ 0 & - & 1 & 0 & 1 \\ 1 & - & 0 & 1 & 0 \\ 1 & - & 1 & 0 & a_2 \end{array}$$

The generalized Table II of transitions and excitation functions for two bits of the register with a number code shift towards higher bits looks like:

TABLE II. TRANSITIONS AND EXCITATION FUNCTIONS FOR TWO BITS OF THE REGISTER WITH A NUMBER CODE SHIFT TOWARDS HIGHER BITS

x_r	Q_t^{i+1}	Q_t^i	Q_{t+1}^{i+1}	Q_{t+1}^i	q_0^{i+1}	q_1^{i+1}
1	0	0	0	1	a_1	0
1	0	1	1	1	0	1
1	1	1	1	0	0	a_2
1	1	0	0	0	1	0



a)

b)

c)

Fig. 6. Structural diagram of a register with a shift towards higher digits (a), a nanocircuit on quantum automata (b) and the results of signal modeling (c) in CAD QCADesigner

Using the transition matrix valid for a flip-flop with separate inputs, let's fill in the columns for the excitation functions (q_0^{i+1} and q_1^{i+1}). It follows from the obtained table that:

at $a_1 = 1$

$$q_0^{i+1} = x_r \bar{Q}_t^i, \quad q_0^{i+1} = \mathrm{maj}(x_r, \bar{Q}_t^i, 0),$$

at $a_2 = 1$

$$q_1^{i+1} = x_r \bar{Q}_t^i, \quad q_1^{i+1} = \mathrm{maj}(x_r, \bar{Q}_t^i, 0).$$

Excitation functions for other bits of the register are defined similarly.

The structural diagram of the register with a shift towards higher digits is shown in Fig. 6.

The total number of quantum cellular automata of the register nanocircuit with a shift towards higher digits is: 167. Dimensions of the quantum cellular automata: 18×18 nm. The distance between the centers of quantum cellular automata is 20 nm. The diameters of the quantum islands are 5 nm.

The total dimensions of the register are: (740×260) nm.

Let us consider a register with a shift in the direction of lower digits, the generalized Table III of transitions and excitation functions of which has the form.

On the basis of the obtained table, the expressions for the excitation functions are compiled:

when $a_1 = 1$

$$q_0^i = x_r \bar{Q}_t^{i+1}, \quad q_1^i = \mathrm{maj}(x_r, \bar{Q}_t^{i+1}, 0).$$

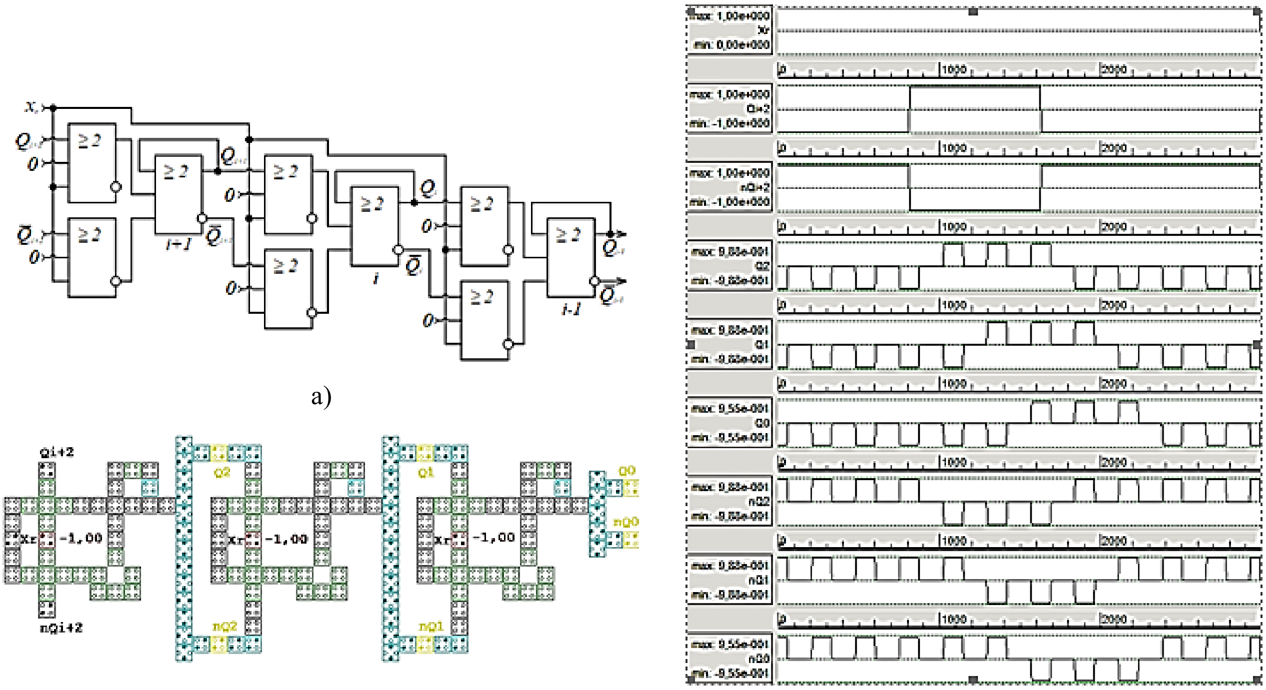
when $a_2 = 1$

$$q_1^i = x_r \bar{Q}_t^{i+1}, \quad q_0^i = \mathrm{maj}(x_r, \bar{Q}_t^{i+1}, 0),$$

In Figure 7 shows the structural diagram of the register with a shift towards lower digits.

TABLE III. TRANSITIONS AND EXCITATION FUNCTIONS FOR TWO BITS OF THE REGISTER WITH A SHIFT IN THE DIRECTION OF LOWER DIGITS

x_r	Q_t^{i+1}	Q_t^i	Q_{t+1}^{i+1}	Q_{t+1}^i	q_0^i	q_1^i
1	0	0	1	0	a_1	0
1	1	0	1	1	0	1
1	1	1	0	1	0	a_2
1	0	1	0	0	1	0



a)

b)

c)

Fig. 7. Structural diagram of a register with a shift towards higher digits (a), a nanocircuit on quantum automata (b) and the results of signal modeling (c) in CAD QCADesigner

The total number of quantum cellular automata of the register nanocircuit: 167. Dimensions of the quantum cellular automata: 18×18 nm. The distance between the centers of quantum cellular automata is 20 nm. The diameters of the quantum islands are 5 nm.

The total dimensions of the register are: (740×260) nm.

V. CONCLUSIONS

Majority elements are one of the most promising directions of increasing reliability and interference resistance when their inputs are affected by random fluctuations in the operation signals of computer systems.

The work implements computer design of sequential-type nanodevices using the QCADesigner automated design system. The goal of layering nanocircuits and increasing their operational reliability has been achieved.

A functionally complete majority system of nanoelements has been created for the computer design of sequential-type nanodevices, including nanotriggers with separate inputs and (based on them) nanoregisters.

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О. С. Мельник, В. О. Козаревич. Одноелектронні послідовностні наносхеми та їх моделі

Запам’ятовуючі наноприводи відрізняються великою різноманітністю мажоритарних тригерних структур, які є базовими фрагментами наносхеми високого рівня інтеграції. У статті описано синтез надійних послідовних нанопристроїв одноелектроніки на основі технології квантових коміркових автоматів. При побудові більшості наносхем з пам'яттю використовується теорія скінченних автоматів. Реалізовано метод комп’ютерного проектування різних типів арифметико-логічних нанопристроїв. Створено високошвидкісні нанореєстри керування паралельної та парафазної дії.

Ключові слова: квантові автомати; мажоритарна логіка; одноелектроніка; нанорегістри; комп’ютерне проектування; модель.

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Кількість публікацій: більше 170 наукових робіт.
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