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MODELING OF TRANSITIONAL PROCESSES IN THE INFORMATION TRANSFORMERS — JOSEPHSON CRYOTRONS

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Abstract. In the present work, we show that logical state controlling of Josephson memory cells (cryotrons) is possible not only by applying external current impulses, but also by means of magnetic flux impulses. By using methods of mathematical modeling, we studied transitional processes in cryotrons during the switching of their logical state and calculated transitional characteristics for the operational temperature $T = 81{,}2$ K. Peculiarities of the Josephson cryotrons' behavior and the effect of the variation of model parameters on direct logical transitions "0" $\rightarrow$ "1" and inverse logical transitions "1" $\rightarrow$ "0" are discussed.

Keywords: Josephson cryotron, information transformer, quantum memory cells, transitional characteristics, logical transition

МОДЕЛЮВАННЯ ПЕРЕХІДНИХ ПРОЦЕСІВ В ІНФОРМАЦІЙНИХ ПЕРЕТВОРЮВАЧАХ — ДЖОЗЕФСОНІВСЬКИХ КРІОТРОНАХ

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Анотація. В роботі показано, що керувати логічним станом джозефсонівських елементів пам'яті (кріотронів) можна не тільки дією зовнішніх імпульсів струму, а також за допомогою імпульсів магнітного потоку. Методами математичного моделювання досліджено перехідні процеси в кріотронах під час зміни їх логічного стану та розраховано перехідні характеристики кріотронів для робочої температури $T = 81{,}2$ K. Виявлено особливості поведінки джозефсонівських кріотронів та досліджено вплив параметрів моделі на прямі логічні переходи "0" $\rightarrow$ "1" та зворотні логічні переходи "1" $\rightarrow$ "0".

Ключові слова: інформаційний перетворювач, квантова комірка пам'яті, джозефсонівський кріотрон, перехідна характеристика, логічний перехід

МОДЕЛИРОВАНИЕ ПЕРЕХОДНЫХ ПРОЦЕССОВ В ИНФОРМАЦИОННЫХ ПРЕОБРАЗОВАТЕЛЯХ — ДЖОЗЕФСОНОВСКИХ КРИОТРОНАХ

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Аннотация. В работе показано, что управлять логическим состоянием джозефсоновских ячеек памяти (криотронов) можно не только действием внешних импульсов тока, а также с помощью импульсов магнитного потока. Методами математического моделирования исследовано переходные процессы в криотронах во время изменения их логического состояния и рассчитаны переходные характеристики криотронов для рабочей температуры T = 81,2 K. Обнаружено особенности поведения джозефсоновских криотронов и исследовано влияние параметров модели на прямые логические переходы “0”$\rightarrow$“1” и обратные логические переходы “1”$\rightarrow$“0”.

Ключевые слова: информационный преобразователь, квантовая ячейка памяти, джозефсоновский криотрон, переходная характеристика, логический переход

Introduction

Superconducting or Josephson cryotrons are promising candidates for being used as composite elements of logical circuits, memory devices and various switches. Their advantages are low energy consumption during the logical state switching (~10^{-18} J), small characteristic sizes (~10^{-2} — 1 μm), high operational speed (the switching time or the commutation time ~10^{-11} s) [1,4,5,6-7]. In computer technology, they are very attractive due to, first of all, their higher operational speed in comparison with traditional elements. Nowadays, the investigations aimed at developing super-high speed computer memory cells based on Josephson tunnel junctions are at the final stage [2,3,8,9,10-12]. In our previous studies [14,15], we developed a mathematical model for Josephson cryotrons (JC) and calculated their transitional characteristics during the logical state switching controlled by external current impulses. The cryotrons were based upon Josephson tunnel junctions made of high-temperature superconductors, which can be used as super-high speed memory cells, with the operational temperature equal to the boiling temperature of nitrogen T = 77 K. We also proposed to control the cryotron’s logical state by magnetic field impulses instead of current impulses. As a result, the transitional characteristics were improved, the commutation time for logical transitions “0”$\rightarrow$“1” and “1”$\rightarrow$“0” was reduced, which lead to the increase of the cryotron’s speed.

Mathematical model of transitional processes in cryotrons

It is known that there are two ways of controlling the logical state of Josephson cryotrons: 1) by means of controlling current impulses; 2) by means of controlling magnetic flux impulses. Let us consider how the logical state of cryotrons is controlled by magnetic flux impulses. In order to understand this controlling mechanism, we use the relation between the critical current of the Josephson tunnel junction (JTJ) I_C and the external magnetic field H_0 or the magnetic flux through the JTJ Φ. The quantities H_0 and Φ are related as $\Phi = H_0 S$, where S is the effective area, through which the magnetic field penetrates into the tunnel junction. The function $I_C(\Phi)$ is well known: $I_C(\Phi) = I_C(0)\left|\dfrac{\sin\frac{\pi\Phi}{\Phi_0}}{\frac{\pi\Phi}{\Phi_0}}\right|$, where $I_C(0)$ is the critical current in the JTJ in the case when $\Phi = 0$ or $H_0 = 0$, and Φ_0 is the magnetic flux quantum.

When the magnetic flux Φ is varied from $\Phi = 0$ to $\Phi = \Phi_0$, the critical current decreases from the value $I_C(0)$ to zero, i.e., by varying the magnetic flux Φ or the external magnetic field H_0 it is possible to effectively change the critical current I_C. By varying the critical current I_C, one can establish $I_C > I_P$, where I_P is the critical current flowing through the cryotron (the cryotron’s operational current), corresponding to zero voltage across the cryotron due to superconducting non-dissipative tunneling of Cooper pairs. In the case of $I_C < I_P$, the non-dissipative tunneling of Cooper pairs is destroyed and a non-zero voltage across the cryotron appears. These processes make up the foundation for creating computer memory cells based on Josephson cryotrons and for developing methods to control the logical state of such cells.

The core of the mathematical model for transitional processes in Josephson cryotrons is the differential equation [14]

$$I_P = I_C \sin\phi + \frac{C\hbar}{2e}\frac{d^2\phi}{dt^2} + \frac{G(V)\hbar}{2e}\frac{d\phi}{dt}, \qquad (1)$$

where I_P is the operational current flowing through the cryotron, I_C is the cryotron's critical current, C is the capacitance of the tunnel junction, $G(V)$ is the conductance of the tunnel junction during single-electron tunneling (generally, the conductance G depends on the voltage across the cryotron V), $\hbar$ is the Planck's constant, e is the electron charge, $\phi(t)$ is the function that describes the time dependence of the difference between the phases of the wave-functions of the superconductors on the both sides of the tunnel junction (phase jump). The function $\phi(t)$ is the unknown function in this differential equation. Having determined $\phi(t)$, one can obtain the main transitional characteristic of the cryotron — the time dependence of the voltage $V(t)$ during the change of the cryotron's logical state — using the equation of the non-stationary Josephson effect

$$V(t) = \frac{\hbar}{2e}\frac{d\phi}{dt} = \frac{\hbar}{2e}\phi'. \qquad (2)$$

The initial conditions for Eq. (1) were: $t = 0$; $\phi = 0$; $\phi' = 0$ or $V = 0$. The dependence of the normal conductance of the tunnel junction on the voltage $G(V)$ were replaced by, according to formula (2), the function $G(\phi')$, which was determined from the VI-characteristic of the JTJ during the single-electron tunneling of charge carriers. For the operational temperature of the cryotron $T = 81{,}2$ K, the VI-characteristic of the JTJ was approximated by a simple mathematical function

$$I(V) = G_0 \cdot \left[0{,}920\cdot V - \frac{0{,}001^{1,4}\cdot 2681\cdot V^{1,4}}{1+(0{,}054\cdot V)^{15,5}}\right], \qquad (3)$$

where G_0 is the normal conductance of the tunnel junction, the parameter that can be changed in the course of modeling and eventually given an optimal value. The logical state of the cryotron was controlled by the change of external magnetic field, which lead to the change of the cryotron's critical current. Mathematically, the change of the critical current was described by the Heaviside function $\eta(t-\tau)$ or the function $e^{-\left(\frac{t-\tau}{\Delta t}\right)^4}$, where τ is the time of application of the controlling impulse, Δt is the duration of the controlling impulse. In the former case, the time dependence of the controlling impulses was given as

$$I_c(t) = I_c(H_0) - \delta I\eta(t-\tau), \qquad (4)$$

where $I_C(H_0)$ is the critical current for the operational magnetic field H_0 and δI is the variation of the critical current, while in the latter case:

$$I_c(t) = I_c(H_0) - \delta I e^{-\left(\frac{t-\tau}{\Delta t}\right)^4}. \qquad (5)$$

After due substitutions, we obtained the working differential equation for calculating the transitional characteristics of the cryotrons:

$$I_p = \frac{C\hbar}{2e}\phi'' + [0{,}920\,\alpha\phi' - \frac{0{,}001^{1,4}\cdot 2681\cdot(\alpha\phi')^{1,4}}{1+(0{,}054\alpha\phi')^{15,5}}]\,G_0 + [\,I_c(H_0) - \delta I\eta(t-\tau)\,]\sin\phi \qquad (6)$$

for the Heaviside function, and

$$I_p = \frac{C\hbar}{2e}\phi'' + [0{,}920\,\alpha\phi' - \frac{0{,}001^{1,4}\cdot 2681\cdot(\alpha\phi')^{1,4}}{1+(0{,}054\alpha\phi')^{15,5}}]\,G_0 + [\,I_c(H_0) - \delta I e^{-\left(\frac{t-\tau}{\Delta t}\right)^4}\,]\sin\phi \qquad (7)$$

for the case when the variation of the critical current is given by the function $e^{-\left(\frac{t-\tau}{\Delta t}\right)^4}$ ($\alpha = \frac{\hbar}{2e}$). During transitional processes, the voltage across the cryotron V or the function ϕ' can be either equal to zero (state "0") or greater than zero (state "1"). However, it was established that during logical transitions "1"$\rightarrow$"0" because of the voltage oscillations the voltage can assume negative values. In such case, for calculating functions $(\phi')^{1,4}$ or $(\phi')^{15,5}$ the function $G(|V|)$ was used instead of $G(V)$. This substitution is valid since Josephson tunnel junctions of the S-I-S type are symmetrical and have symmetrical VI-characteristics, i.e., their conductance depends only on the magnitude of the applied voltage and does not depend on the polarity of the voltage.

Transitional characteristics of the cryotrons

In order to develop the mathematical model of transitional processes in Josephson cryotrons during the change of their logical state controlled by external magnetic flux impulses and to obtain test transitional characteristics, the field induced change of the critical current of the cryotron was given by a simple mathematical function, namely, by the Heaviside function $\eta(t-\tau)$. The transitional characteristics of the cryotrons were obtained by solving the working differential equation (6). The time dependence of the critical current was given by the function $I_c(t) = I_c(H_0) - \delta I_1\eta(t-\tau_1) + \delta I_2\eta(t-\tau_2)$. In Fig. 1, one of the calculated transitional characteristics is displayed. At the initial time $t = 0$, the cryotron was in the logical state “0”, with the voltage $V = 0$ as the operational current $I_p = 6$ mA was less than the initial critical current $I_c(H_0) = 10$ mA. Initially, one observed damped voltage oscillations of small amplitude on the transitional characteristic $V(t)$, which can be explained by the cryotron entering into a stationary operational regime. At the time $\tau_1 = 10$ ps, affected by the controlling magnetic field impulses, the critical current decreased in a step-like manner by $\delta I_1 = 9$ mA and became less than the operational current $I_p = 6$ mA. This lead to the logical transition of the cryotron from the state “0” into the state “1”; the voltage V_0 settled across the cryotron and remained unchanged as the time passed. The characteristic time of the logical transition “0”$\rightarrow$“1”, which we will regard as the commutation time of the cryotron, $\Delta\tau_1 \approx 3$ ps.

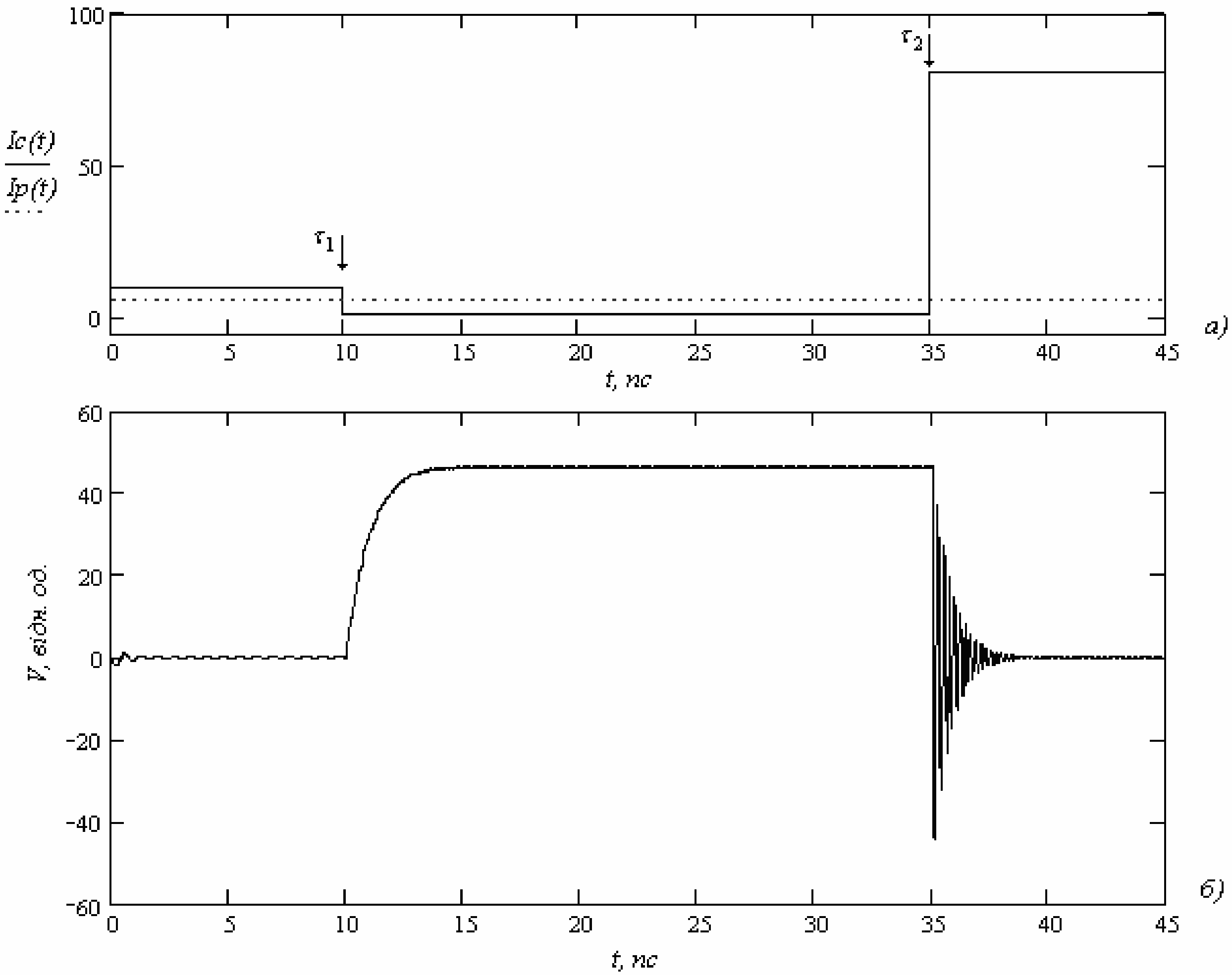

Fig. 1. The time dependence of the critical current of the cryotron I_c (a) and of the voltage across the cryotron V (b) during the logical transition “0”$\rightarrow$“1”$\rightarrow$“0”, corresponding to the following model parameters: the initial critical current $I_c(H_0) = 10$ mA; the operational current (dashed line) $I_p = 6$ mA; the capacitance of the tunnel junction $C = 0{,}3$ pF; the normal conductance of the tunnel junction $G_0 = 0{,}9\ \Omega^{-1}$; the variation of the critical current during the transition “0”$\rightarrow$“1” $\delta I_1 = 9$ mA; the time when the critical current changes during the transition “0”$\rightarrow$“1” $\tau_1 = 10$ ps; the variation of the critical current during the transition “1”$\rightarrow$“0” $\delta I_2 = 80$ mA; the time when the critical current changes during the transition “1”$\rightarrow$“0” $\tau_2 = 35$ ps

At the time τ_2 = 35 ps, a controlling magnetic flux impulse increased the critical current of the cryotron by δI_2 = 80 mA with respect to its previous value, which initiated a logical transition "1" $\rightarrow$"0" in the cryotron. The voltage changed from the value of V_0 to V = 0. In this case, the voltage was not changing smoothly, but instead its decrease was accompanied by damped voltage oscillations, whose initial amplitude was close to V_0. Analogous damped voltage oscillations during logical transitions "1"$\rightarrow$"0" were observed in our previous studies [14,15], were we obtained by means of mathematical modeling transitional characteristics of the cryotrons when controlling their logical state by current impulses. The commutation time of the cryotron, defined as the time elapsed from the moment of the controlling impulse application to the moment when the voltage oscillations have disappeared and the zero voltage has settled across the cryotron, was $\Delta\tau_2 \approx$ 4 ps. Comparing the commutation times $\Delta\tau_1$ and $\Delta\tau_2$, one concludes that they are approximately equal. In Ref. 15, the commutation time of an inverse logical transition "1"$\rightarrow$"0" $\Delta\tau_2$ was found to be 5 — 10 times greater than the commutation time $\Delta\tau_1$ of a direct logical transition "0"$\rightarrow$"1". Assuming that the cryotron's operational speed is determined by the greater commutation time of the commutation times $\Delta\tau_1$ and $\Delta\tau_2$, one concludes that the cryotrons controlled by magnetic field impulses will be more advantageous than the cryotrons whose logical state is controlled by current impulses.

It was established that for the transition "1"$\rightarrow$ "0" the variation (increase) of the critical current must be 10 times greater than the variation (decrease) of the critical current during the transition "0"$\rightarrow$"1" as these transitions are not symmetrical. The former transition is due to the destruction of the Cooper pairs superconducting tunneling through the potential barrier, whereas the latter transition is due to the superconducting tunneling resumption. Obviously, it is easier to get the superconducting tunneling destroyed than to get it resumed [16].

Investigating the calculated transitional characteristics $V(t)$ of the cryotrons during the change of their logical state, we found out that a cryotron, having accomplished a logical transition "0"$\rightarrow$ "1", can remain in the state "1" even when the critical current assumes again in a certain time its initial value (Fig. 2).

The cryotrons behaved analogously in the case when after the logical transition "1"$\rightarrow$"0" the critical current decreased to its initial value. As one observes in Fig. 2, at the time τ_1 = 9 ps the critical current I_c becomes less than the operational current I_p and in 2 ps returns to its initial value $I_c(H_0)$. As a result, the cryotron undergoes a logical transition "0"$\rightarrow$"1" and afterwards, even though the value of I_c is greater than I_p, remains in the state "1". On one hand, this contradicts, in a way, the principles of the cryotrons' operation, while, on the other hand, if such a behavior is realized in practice, the control over the cryotrons' logical state will become considerably easier.

The characteristic commutation time for the logical transition "0"$\rightarrow$"1" is $\Delta\tau_1 \approx$ 2,5 ps. At the time τ_3 = 29 ps, the critical current I_c is increased in an impulse-like manner and returned to the initial value $I_c(H_0)$, which results in a logical transition "1"$\rightarrow$"0", with the commutation time $\Delta\tau_2 \approx$ 4 ps. However, in this case the voltage decrease is accompanied by damped voltage oscillations, with the initial amplitude comparable with V_0.

We have established that the logical transition "1"$\rightarrow$"0" cannot be accomplished without voltage oscillations at the cryotron. When the amplitude of these oscillations was less (much less) than the voltage V_0, undamped voltage oscillations were observed and the cryotron did not change its logical state. A logical transition "1"$\rightarrow$"0" was only possible when the controlling impulses were causing voltage oscillations with an amplitude close to V_0; the undamped oscillations in this case were giving place to damped ones, and only afterwards the cryotron was changing its state to the logical "0".

Of course, the controlling impulses of an ideal rectangular shape that we used in the mathematical model were just the first step in the course of the model's development. In the following, we replaced the step-like impulses of an ideal shape by smooth ones, which can be given by the mathematical expression e^{-t^4}. These impulses were chosen among a series of impulses $e^{-t^2}, e^{-t^4}, e^{-t^6}, e^{-t^8}$, ... basing on the following considerations. Firstly, the impulses e^{-t^4} are more localized in time compared with the impulses e^{-t^2}. Secondly, the mathematical expressions of the impulses e^{-t^4} are more convenient to work with than those of e^{-t^6} or e^{-t^8} and do not overcomplicate the working differential equations.

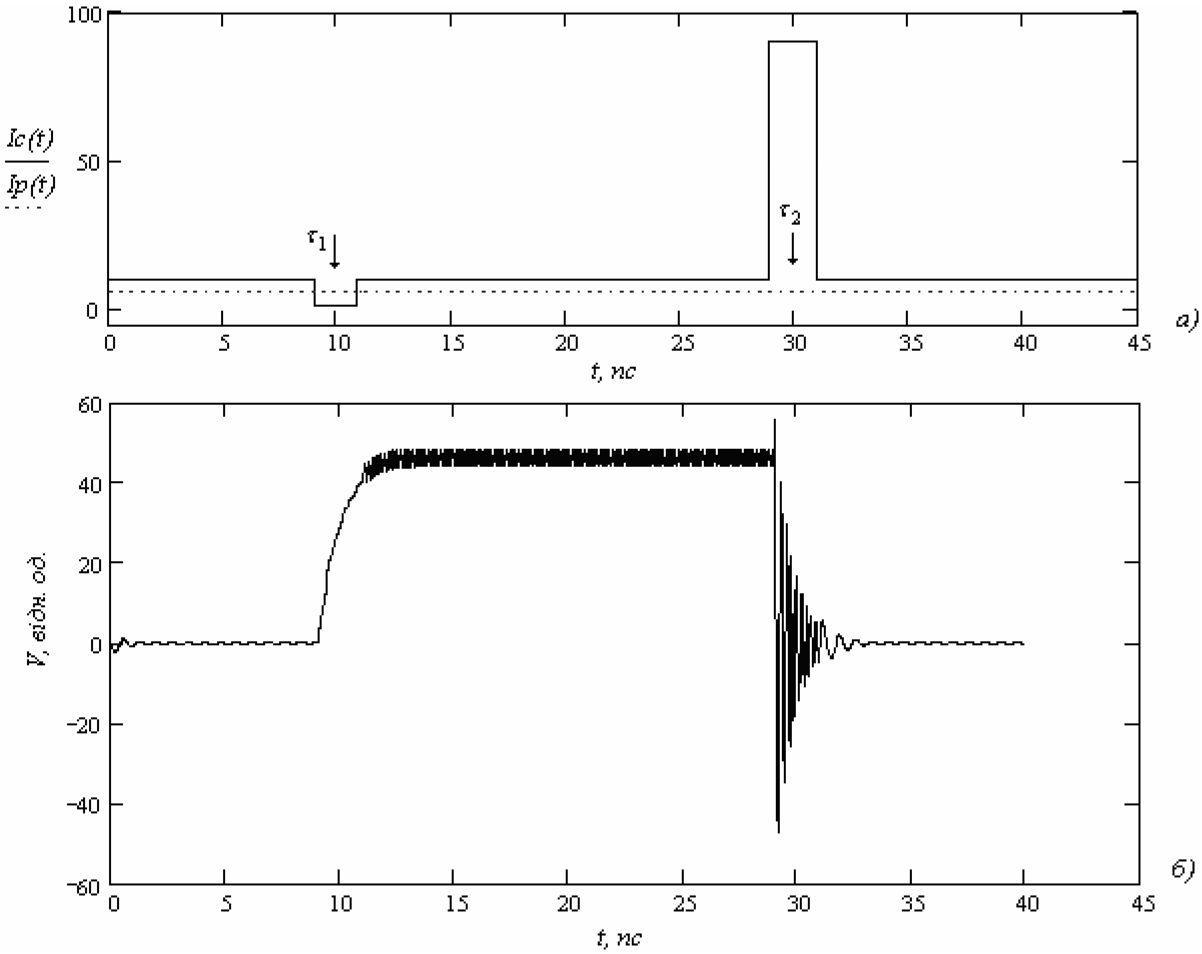

Fig. 2. The time dependence of the critical current of the cryotron I_c (a) and of the voltage across the cryotron V (b) during the logical transition "0" → "1" → "0", corresponding to the following model parameters: the initial critical current $I_c(H_0)$ = 10 mA; the operational current (dashed line) I_p = 6 mA; the capacitance of the tunnel junction C = 0,3 pF; the normal conductance of the tunnel junction G_0 = 0,9 Ω^{-1}; the variation of the critical current during the transition "0" → "1" δI_1 = 9 mA; the time when the critical current decreases for the logical transition "0" → "1" τ_1 = 9 ps; the time when I_c returns to its initial value τ_2 = 11 ps; the variation of the critical current during the transition "1" → "0" δI_2 = 80 mA; the time when the critical current I_c increases for the logical transition "1" → "0" τ_3 = 29 ps; the time when I_c returns to the initial value τ_4 = 31 ps

In Fig. 3, we present the time dependence of the critical current of the cryotron $I_c(t)$ (a) and of the voltage across the cryotron $V(t)$ (b) during the logical transition "0" → "1" → "0" for the case when $I_c(t)$ was smoothly modified by controlling impulses. $I_c(t)$ was given by the mathematical function e^{-t^4}, namely, $I_c(t) = I_c(H_0) - \delta I_1 e^{-\left(\frac{t-\tau_1}{\Delta t}\right)^4}$ for the logical transition "0" → "1" and $I_c(t) = I_c(H_0) + \delta I_2 e^{-\left(\frac{t-\tau_2}{\Delta t}\right)^4}$ for the logical transition "1" → "0". The commutation time of the cryotron $\Delta\tau_1$ during the logical transition "0" → "1" was 4 ps, which is practically the same value as obtained from the modeling involving rectangular impulses. The characteristic commutation time for the logical transition "1" → "0" was $\Delta\tau_1 \approx 4,5$ ps. These results do not differ in any considerable way from the results obtained by using rectangular impulses.

Conclusions

By using the basic principles of controlling the Josephson cryotron's logical state by variation of the critical current by means of external magnetic field impulses or magnetic flux impulses, we improved the mathematical model of transitional processes in cryotrons during the change of their logical state and calculated transitional characteristics of the cryotrons. The results of the mathematical modeling of transitional processes and the analysis of the calculated transitional character-

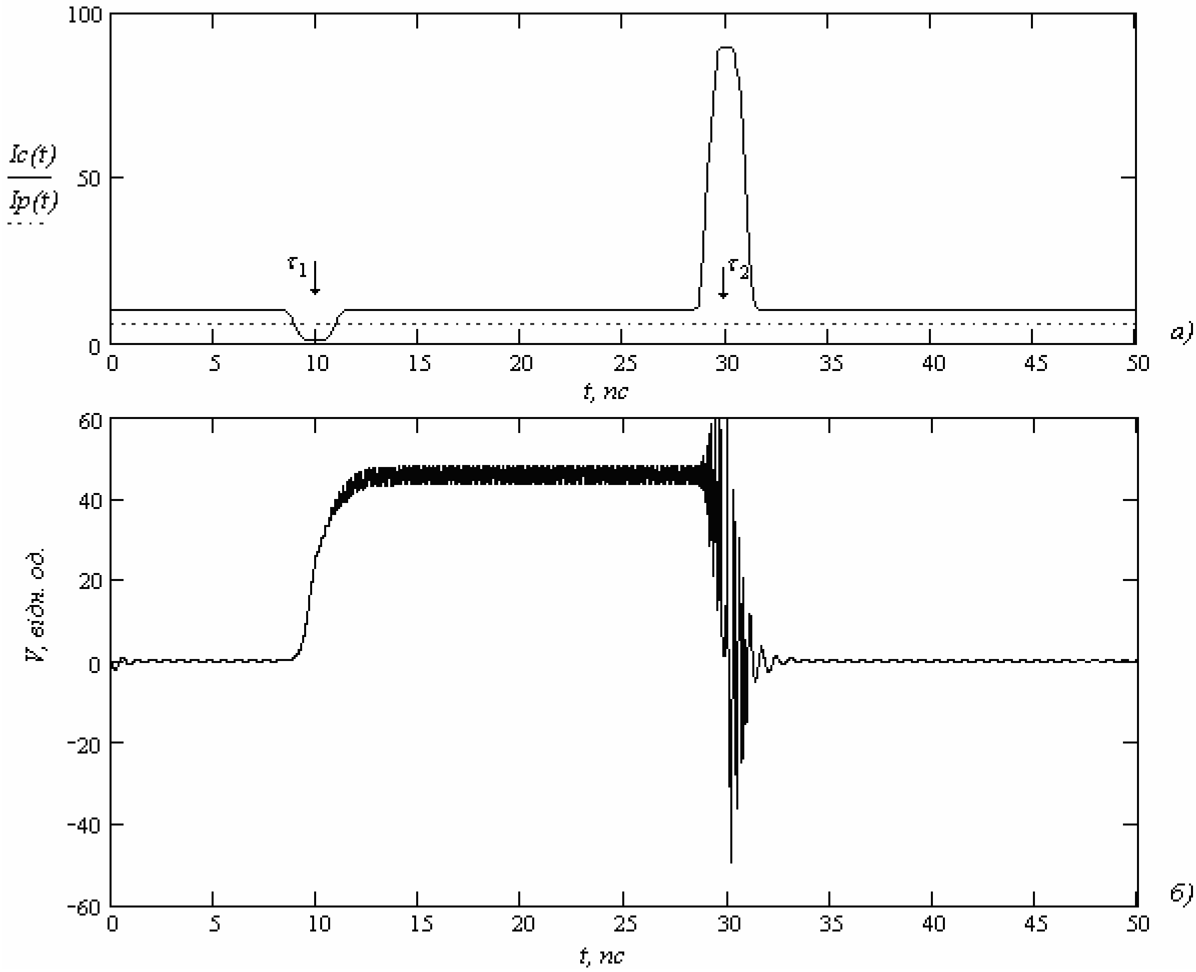

Fig. 3. The time dependence of the critical current of the cryotron I_c (a) and of the voltage across the cryotron V (b) during the logical transition "0"→"1"→"0", corresponding to the following model parameters: the initial critical current $I_c(H_0)$ = 10 mA; the operational critical current I_p = 6 mA; the capacitance of the tunnel junction C = 0,3 pF; the normal conductance of the tunnel junction G_0 = 0,9 Ω^{-1}; the variation of the critical current during the transition "0"→"1" δI_1 = 9 mA; the time of the controlling impulse application during the transition "0"→"1" τ_1 = 10 ps; the variation of the critical current during the transition "1"→"0" δI_2 = 80 mA; the time of the controlling impulse application during the transition "1"→"0" τ_2 = 30 ps; the average duration of the controlling impulses $\Delta t_1 = \Delta t_2$ = 1 ps (the time of the controlling impulse application is defined as the time when the value of I_c reaches its minimum or maximum)

istics lead us to the following conclusions: 1) the considered method of controlling the logical state of cryotrons has more advantages compared to the alternative methods since within this method the commutation times for logical transitions "0"→ "1" and "1"→"0" are almost equal; 2) for a stable operation of the cryotrons, it is necessary to have the amplitude of the voltage oscillations reach the voltage value in the logical state "1"; 3) for stable logical transitions "0"→"1", lowering of the critical current below the operational current is not necessary; these transitions can be accomplished as a result of a transitional process initiated by a short magnetic flux impulse. The requirements for logical transitions "1"→"0" are analogous. Our results can be used for the development and construction of quantum memory cells — Josephson cryotrons.

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