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BOUNDARY SURFACE OF MEMORY FOR SMOOTH I–V CHARACTERISTICS

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In this paper we investigate the impact of change in expression of *I–V* characteristics of non-linear elements constituting multiple–valued memory, on the shape of boundary surface. Boundary surface changes are investigated for a such load plane $R > 0$, when multiple intersection of *I–V* surfaces of both elements gave rise to other new singularities. Simultaneously we monitor also change the nature of singularity, which has a great influence on the boundary surface morphology. Results showed, that both the piece-wise linear as well as polynomial expression of *I–V* characteristics the elements are appropriate for multiple–valued memory.

Key words: multiple valued memory, boundary surface, load plane, eigenvalue.

ГРАНИЧНА ПОВЕРХНЯ ПАМ'ЯТІ ДЛЯ ГЛАДКИХ I–V ХАРАКТЕРИСТИК

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Роботу присвячено дослідженню важливості змін у виразах I–V характеристик нелінійних елементів, з яких складається багатозначна пам'ять, на форму граничної поверхні. Зміни граничної поверхні досліджені для таких навантажувальних поверхонь $R > 0$, коли багаторазові перетини поверхонь I–V обох елементів дають зростання кількості нових особливих точок. Одночасно виконується моніторинг зміни природи особливої точки, яка має значний вплив на морфологію граничної поверхні. Результати показали, що і лінійноламана характеристика, і поліноміальний вираз елементів I–V характеристики є прийнятними для багатозначної пам'яті.

Ключові слова: багатозначна пам'ять, гранична поверхня, навантажувальна площина, характеристичне число.

PROBLEM STATEMENT. For the fast calculation of differential equations system without a computer and a relatively accurate approximation of any part of the *I–V* characteristic of the elements, there was suggested in work [1] a procedure for the approximation of any part of the *I–V* characteristic of the element using absolute values. Thus it was possible to create a piece-wise linear (PWL) *I–V* characteristics of transistors, tunnel diodes (TD) and Chua´s diode. In work [2] has been shown influence of change the size of *R* as the load plane in multiple–valued (MV) memory on the number and nature of singularities. Non-linear elements – resonant tunneling diodes (RTD) were expressed as PWL there. The increase the number of singularities led to the unusual case – breaking regular alternation of the singularities: stable – unstable – stable – ... (S–U–S–...). Therefore the question arose: will the same morphology of boundary surface (BS) maintain together with the nature of singularities, when *I–V* characteristics will express as polynomial and thus smooth function? Does the PWL expression of *I–V* characteristics affect the formation of unstable singularity S3 [2] (in this paper concerning singularity 5), which should be in terms of regular alternation of singularities S–U–S–... stable singularity? Do points of discontinuity PWL characteristics affect the formation of unstable singularity S3? In the next section we propose such *I–V* characteristics, that should the most exact approximate the PWL characteristics, we also compare calculated BS and possible occurrence the unwanted unstable singularity with the case published in [2].

EXPERIMENTAL PART AND RESULTS OBTAINED. *Studied Multiple valued logic memory.* elementary MV memory cell is shown in Fig. 1, and is described by system of equations (1). Nonlinear elements have PWL *I–V* characteristics of RTD, Fig. 2,a. Their parameters are given in [2]. Projections *I–V* areas in the plane i, u_2, indicating the Fig. 2,b, where at $R = 0$ is generated by five singularities, while S1, S2 and S3 are stable singularity. They are separated by unstable singularities N1 and N2. The authors suggested that a further contribution to the subsequent conduct found by the work [3] coefficients for the expression of *I–V* characteristics of RTD ninth degree polynomial (2).

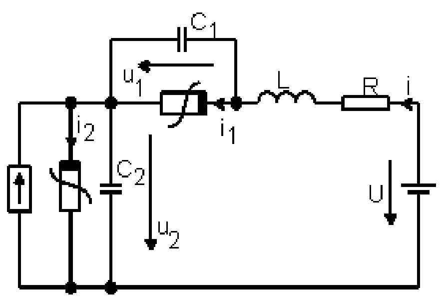

Figure 1 – Model of memory cell. Control pulse we consider ΔI = 0

$$\begin{aligned} L\left(\frac{di}{dt}\right) &= U - Ri - (u_1 + u_2) \equiv Q_1 \\ C_1\left(\frac{du_1}{dt}\right) &= i - f_1(u_1) \equiv Q_2 \\ C_2\left(\frac{du_2}{dt}\right) &= i - f_2(u_2) + \Delta I \equiv Q_3 \end{aligned} \qquad (1)$$

$$f_k(u_k) = \sum_{i=1}^{9} {}^k a_i . u_k , \qquad (2)$$

where a_i are coefficients of appropriate power. Similarly as for PWL in Fig. 2,a) holds, if superscript $k=1$ it concerns load, if $k=2$ it concerns element.

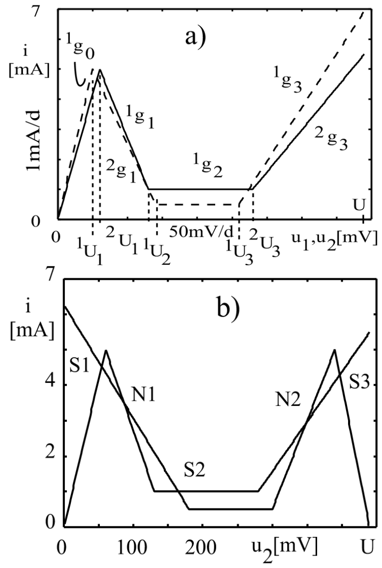

Figure 2 – Comparison *I–V* characteristics of RTD element (solid line) and load (dashed line) b) Present singularities in the projection into the i, u_2 plane when R = 0

For calculation the coefficients in Matlab was used Newton's interpolation method with coefficients given by (3) and (4).

Element:

$$a_1 = 0{,}292;\ a_2 = -5{,}68;\ a_3 = 45{,}8;$$
$$a_4 = -193{,}99;\ a_5 = 456{,}26;\ a_6 = -562{,}33; \quad (3)$$
$$a_7 = 280{,}84\ ;\ a_8 = 5{,}64;\ a_9 = -2{,}85.$$

Load:

$$a_1 = 0{,}306;\ a_2 = -6{,}27;\ a_3 = 53{,}46;$$
$$a_4 = -242{,}27;\ a_5 = 613{,}38;\ a_6 = -814{,}52; \quad (4)$$
$$a_7 = 437{,}72;\ a_8 = 8{,}16;\ a_9 = -4{,}44.$$

Fig. 3,a illustrates approximation *I–V* characteristic of element and Fig. 3,b approximation of the load. Projection *I–V* surfaces into i, u_2 plane shows Fig. 4 when R = 0, where again is present five singularities of the same character and designations like in Fig. 2,b).

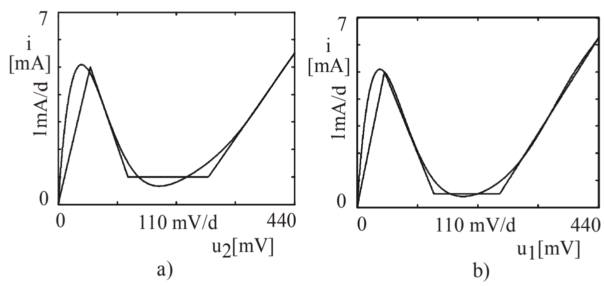

Figure 3 – View of *I–V* characteristics approximated using algebraic polynomial (2) compared with RTD as a) the element – parameters (3); b) the load – parameters (4)

Comparison of BS cross–sections. In this section we show a comparison of BS cross-sections when PWL and smooth *I–V* characteristics are used. Sections were calculated using grid technique, which means that the appropriated projection plane will be divided to the NxN points [4].

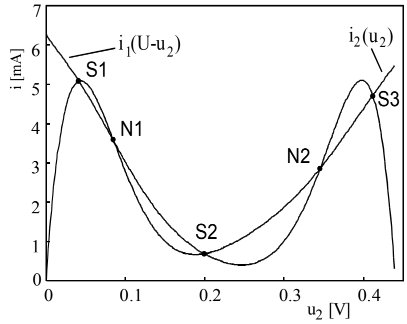

Figure 4 – Present singularities in the projection into the i, u_2 plane when R = 0

These points will represent N^2 of initial conditions for calculation trajectories of system (1). Calculation of the trajectory is terminated when the representative point is located in the vicinity of one of the attractors – stable singularities. Grids presented below were calculated in raster 220x220 points using Matlab software. In work [3] in Fig. 4 we showed the case, when for R = 100 Ω singularity S3 arose (in this paper in Fig. 5 it is singularity 5), which in terms of regular alternation of singularities S–U–S–… should be stable singularity. Cross-section was carried through current level ^5i = 2,28 mA, which is a current coordinate of singularity 5. Singularities denoted by odd number should be stable, and singularities denoted by even number should be unstable. All singularities correspond to the stability assumption, only singularity 5 was an exception.

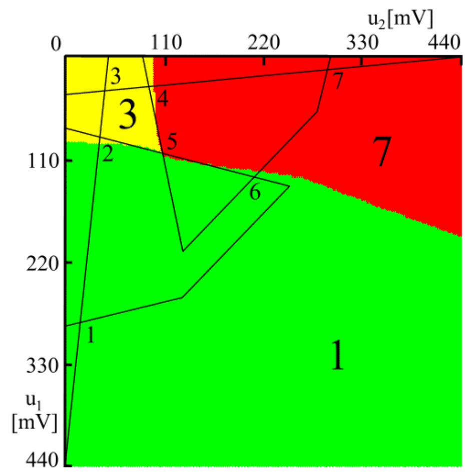

Figure 5 – Cross–section of BS through current level appropriate to singularity 5 (^5i = 2,28 mA) for R = 100 Ω, $C_{1,2}$ = $1\cdot10^{-13}$ F, L = $1\cdot10^{-10}$ H and PWL *I–V* characteristics of RTD. Capital numbers 1, 3 and 7 depicts regions of attractivity for stable singularities 1, 3 and 7. Singularity 5 is unstable

When we use the smooth *I-V* characteristics expressed by ninth grade polynomial, there was calculated cross-section of BS (Fig. 6) for $R = 100\ \Omega$ and current level ^{5}i = 3,9 mA using the same technique. As can be seen from the projection of intersections *I–V* surfaces of both elements into the plane u_1, u_2, also in this case the singularity 5 is unstable, because it lies on the boundary of three regions of attractivity. Eigenvalues for the singularity 5 proving its unstability are listed also in Tab. 1.

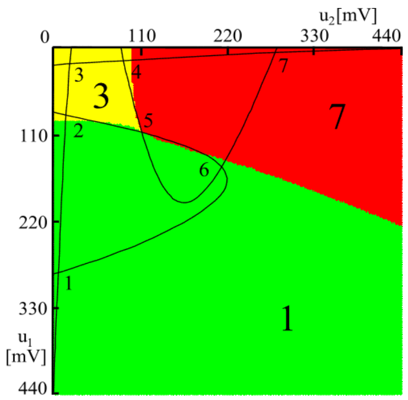

Figure 6 – Cross–section of BS through current level appropriate to singularity 5 (^{5}i = 3,9 mA) for $R = 100\ \Omega$, $C_{1,2} = 1\cdot10^{-13}$ F, $L = 1\cdot10^{-10}$ H. *I–V* characteristics of RTD are smoth. Capital numbers 1, 3 and 7 depicts regions of attractivity for stable singularities 1, 3 and 7. Singularity 5 is again unstable

CONCLUSIONS. As shows Fig. 5 and Fig. 6 there is no significant difference between cross–sections of BS of memory represented by PWL and polynomial models of TD *I–V* characteristics. Neither points of discontinuity occurring as break points in PWL *I–V* characteristics, nor the mathematical expression of *I–V* characteristics of RTD, do not affect the formation of unstable singularity 5 and shape of BS. It is therefore the matter of creator of the simulation program, which model of the *I–V* characteristic would prefer. In general, he get the same results.

Table 1 – Eigenvalues of singularity 5

Singularity 5	
λ_1	–8,46614001843699
λ_2	3,02847397209286
λ_3	4,58588308560323

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ПРЕДЕЛЬНАЯ ПОВЕРХНОСТЬ ПАМЯТИ ДЛЯ ГЛАДКИХ I-V ХАРАКТЕРИСТИК

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Работа посвящена исследованию важности изменений в выражениях для I–V характеристик нелинейных элементов, из которых состоит многозначная память, на форму предельной поверхности. Изменения граничной поверхности исследованы для таких нагрузочных поверхностей $R > 0$, когда многократное пересечение поверхностей I–V обоих элементов дают увеличение количества новых особых точек. Одновременно производится мониторинг изменения природы особой точки, которая имеет большое влияние на морфологию предельной поверхности. Результаты показали, что и линейноломаная характеристика, и полиномиальное выражение элементов I–V характеристики являются приемлемыми для многозначной памяти.

Ключевые слова: многозначная память, предельная поверхность, нагрузочная плоскость, характеристическое число.

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