UDC 621.797: 621.664

BOUNDARY SURFACE AND LOAD PLANE OF THE TERNARY MEMORY

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The item deals with the impact of the load plane on circuit of multiple valued memory. If the multiple-value memory consists of two one-peak resonant tunnel diodes, change in the number of singularities can be achieved by resizing *R* without additional circuit modifications. This change will become evident by change of the boundary surface morphology, which even without calculating their eigenvalues in Matlab indicates stability or instability of newly formed singularities. When *I-V* surfaces of both elements multiple intersect due to $R>0$, there can occur such case, that the stable singularities will be less than unstable, what cannot be achieved when $R=0$.

Key words: state space, load plane, singularity, ternary memory, stable limit cycle, resonant tunnel diode.

Introduction. References [1] - [5] show analysis of multiple-valued logic memory which consist of two series connected tunnel diodes or resonant tunnel diodes (fig.1) when $R=0$. The results of the investigation were surprising because of the presence of undesirable SLC, boundary surface (BS) fragmentation, and also presence of a saddle virtual singularity [6], [7] which makes it impossible controlling memory [8]. Work [9] pointed out the change in the number of singularities when parameter *R* is changed. Thus it was possible to reach from the original five singularities (fig.1), only three (binary memory-fig.2), or even seven singularities. This would mean that only by a change of *R*, without changing the *I-V* characteristics, ternary memory can be changed to binary or quaternary memory. As in works [1-5] for $R=0$, also in these cases for $R>0$ were made cross-sections of BS with surprising results mentioned in this article. Multiple valued memory can be used also in modern production technologies [10] - [13].

Circuit and its description. The analysed circuit in fig.1 is described by the system of state equations (1). The $i_2(u_2)$ and $i_1(u_1)$ represent the piecewise-linear (PWL) characteristics of the element and the load, respectively given by the expression (2)

$$
\begin{aligned}
L\left(\frac{di}{dt}\right) &= U - Ri - (u_1 + u_2) \equiv Q_1 \\
C_1\left(\frac{du_1}{dt}\right) &= i - i_1(u_1) \equiv Q_2 \qquad (1)\\
C_2\left(\frac{du_2}{dt}\right) &= i - i_2(u_2) \equiv Q_3
\end{aligned}
$$

$$
\begin{aligned}
i_j(u_j) = {} & \frac{1}{2}\left({}^j g_0 + {}^j g_3\right)u_j + \frac{1}{2}\Big[\left({}^j g_1 - {}^j g_0\right)\,|u_j - U_1| + \\
& \left({}^j g_2 - {}^j g_1\right)\,|u_j - U_2| + \left({}^j g_3 - {}^j g_2\right)\,|u_j - U_3|\Big] - \qquad (2)\\
& \frac{1}{2}\Big[\left({}^j g_1 - {}^j g_0\right)U_1 + \left({}^j g_2 - {}^j g_1\right)U_2 + \left({}^j g_3 - {}^j g_2\right)U_3\Big]
\end{aligned}
$$

where ${}^j g_m$ are the conductances of the segments of the PWL characteristics and ${}^j U_k$ are the break points. Here $m= 0, 1, 2, 3$ and $k= 1, 2, 3$. Indexes $j=1$ and $j=2$ correspond to the load and the element, respectively. The parameter values corresponding to element and load device are as follows: ${}^1g_0=0,0833$; ${}^1g_1=-0,0571$; ${}^1g_2=0$; ${}^1g_3=0,0281$; ${}^2g_0=0,1$; ${}^2g_1=-0,05$; ${}^2g_2=0$; ${}^2g_3=0,032$ [S]; ${}^1U_1=60$; ${}^1U_2=130$; ${}^1U_3=280$; ${}^2U_1=50$; ${}^2U_2=140$; ${}^2U_3=260$ [mV]. (3)

The bias voltage of the circuit is $U=440mV$ and control pulse $\Delta I=0$.

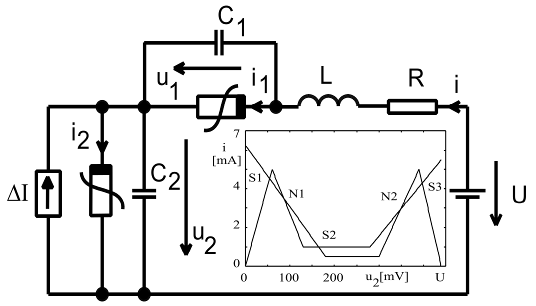

Figure 1 - Model of the analysed circuit and projection of *I-V* characteristics and singularities into plane i,u_2

Influence of resistance *R* on the character of singularities. Geometric interpretation of resistivity $R>0$ from work [6] is presented in fig.2.

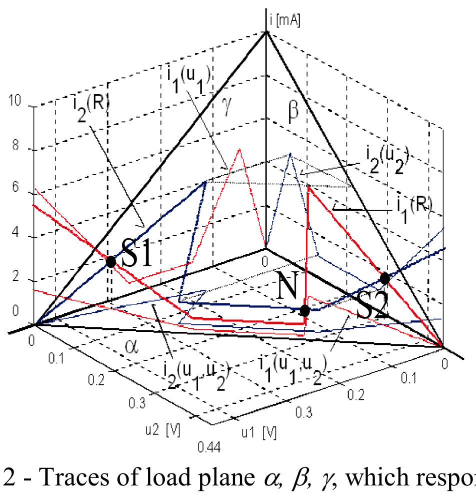

Figure 2 - Traces of load plane *α, β, γ*, which respond to equation $Q_1=0$ (1). Singularities S_1, *N*, S_2 lies on load plane $Q_1=0$. The parameter values of $i_1(u_1)$ and $i_2(u_2)$ is in the previous text, with $R=44\Omega$

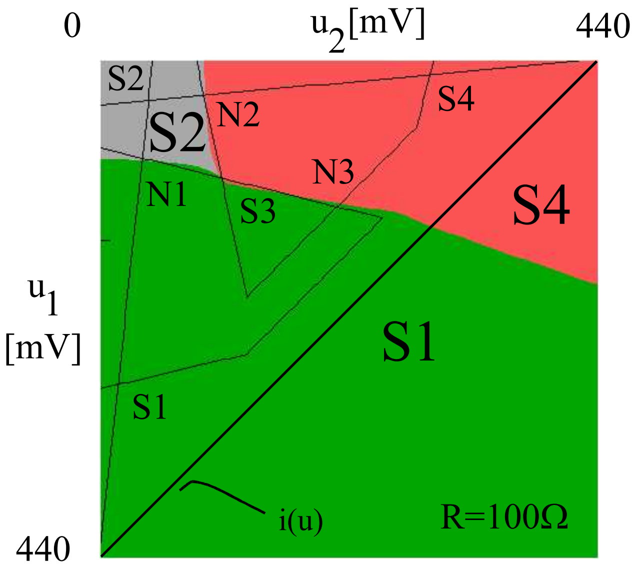

Figure 3 Cross-section of BS for current level corresponding to current level of singularity *S3* ($^{S3}i=2.28mA$). Denotation *i(u)* represents trace of load plane when *R=0*, or trace α when *R=100*Ω.

For *R=100*Ω, *L=1e-10*H and *C=C1=C2=2,6e-13*F was obtained even seven singularities. So far, there always has been followed the change a sequence of singularities in the physical circuits: stable - unstable - stable etc. This was true for memories with positive and also negative load. Therefore we denoted also in this case the expected stable singularities by symbol *S* and unstable by symbol *N*. The number following symbol *S* and *N* indicates the order of stable or unstable singularity, like in fig.1. Fig.3 shows projection of intersection *I-V* planes into u_1,u_2 plane, together with BS cross-section for a current level of singularity *S3* for $^{S3}i = 2,28$ mA.

Fig.3 shows only three color areas instead of four - for attractors denoted by capital letters. According to fig.3 singularity *S3* lies on the boundary of three regions of attractivity and therefore it can not be stable. To verify the accuracy of the simulation there were calculated eigenvalues of all singularities with help of Matlab. All of them are listed in Table 1. From Table 1 it is clear that *S2* (and similarly also *S1* and *S4*) are really stable singularities – λ_1, λ_2, $\lambda_3 > 0$ and *N1* (and similarly also *N2* and *N3*) are unstable - saddle singularities because $\lambda_1 > 0$ and λ_2, $\lambda_3 < 0$.

Signs of eigenvalues for *S3*, however, show in comparison with *N2* some inversion with the knowledge that singularity *S3* can not be truly stable singularity. Thus, there arises a natural question of the impact of the negative differential resistance (NDR) area of the element and the load on the character of singularity formed by intersections of NDR areas when *R=0* or *R>0*. There were proposed also another two structures this once the quaternary memory for comparison with previous example.

Table 1 - Eigenvalues of singularities when *R=100* Ω

	S1
λ_1	-8.805658515540415e+11
λ_2	-4.041794221742470e+11
λ_3	-1.587162647332503e+11
	N1
λ_1	1.613194157448778e+11
λ_2	-3.912351708589386e+11
λ_3	-8.981611679628628e+11
	S2
λ_1	-3.442835209177844e+11
λ_2	-5.184580681185036e+11
λ_3	-8.422584109637107e+11
	N2
λ_1	1.889942627330766e+11
λ_2	-4.649302854271197e+11
λ_3	-8.890639773059575e+11
	S3
λ_1	2.087673466538174e+11
λ_2	1.355735634806396e+11
λ_3	-9.324178332113801e+11
	N3
λ_1	1.647994698193528e+11
λ_2	-4.857757784109082e+10
λ_3	-9.239141996705698e+11
	S4
λ_1	-1.459626569961180e+11
λ_2	-4.763648402352091e+11
λ_3	-8.703648104609810e+11

Quaternary memory

For creation *I-V* characteristics of the second structure was used the same relation (2) with following parameters:

$^1g_0=0,0833;$ $^1g_1=-0,0571;$ $^1g_2=-0,012;$ $^1g_3=0,0281;$ $^2g_0=0,0833;$ $^2g_1=-0,0571;$ $^2g_2=-0,012;$ $^2g_3=0,0281$ *[S]*; $^1U_1=60;$ $^1U_2=120;$ $^1U_3=250;$ $^2U_1=60;$ $^2U_2=120;$ $^2U_3=250$ [mV]. (4)

and for creation *I-V* characteristics of the third structure was also used relation (2) with parameters:

$^1g_0=0,0833;$ $^1g_1=-0,0571;$ $^1g_2=-0,012;$ $^1g_3=0,0281;$ $^2g_0=0,1;$ $^2g_1=-0,05;$ $^2g_2=-0,001;$ $^2g_3=0,032$ *[S]*; $^1U_1=60;$ $^1U_2=120;$ $^1U_3=250;$ $^2U_1=50;$ $^2U_2=145;$ $^2U_3=250$ [mV]. (5)

Projections the *I-V* characteristics into the plane i ,u_2 for *R=0* and parameters (4) or (5) are shown in fig. 4a) or fig.5a). In both cases the singularity N2, similarly as in fig.3 when $R=100\Omega$, consists of two segments with the NDR. Singularities denoted with the letter S or N are stable or unstable and the number indicates their order like in fig.1.

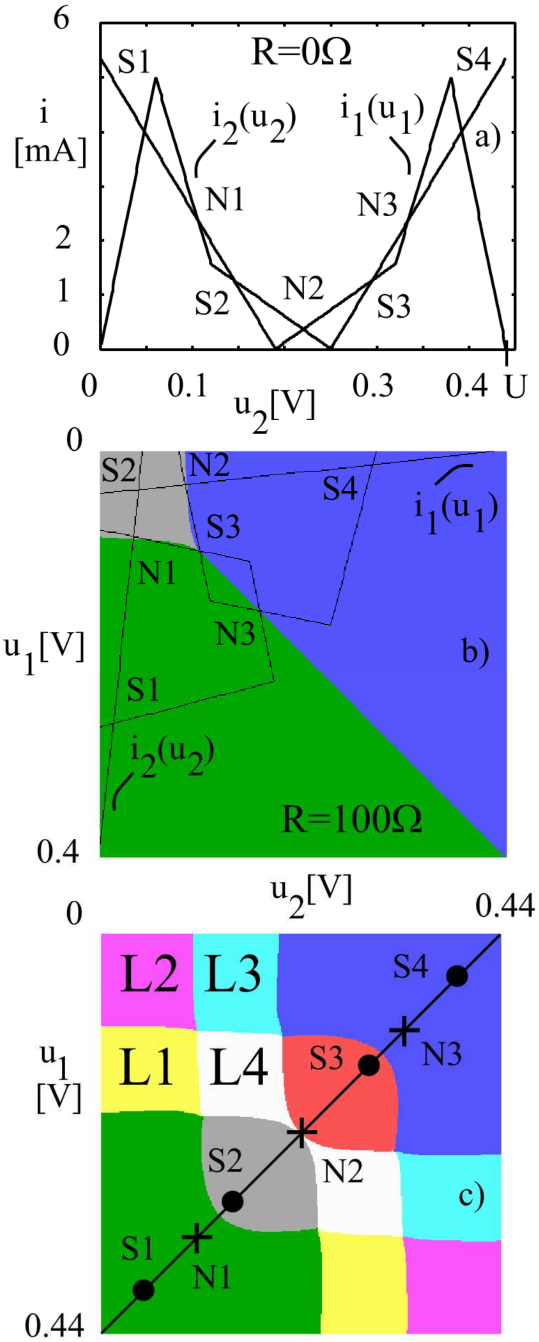

Figure 4 a) *I-V* characteristics in the projection into the i,u_2 plane at $R=0$, b) The projection of cross-sections of *I-V* areas into the plane u_1,u_2 at $R=100\Omega$, and cross-section of S3 for ${}^{S3}i=2,23$ mA. c) Cross-sections of BS in plane u_1,u_2 at $i=0$mA, $R=0$.

In both cases it is evident alternation of singularities: stable – unstable – stable, etc. Even singularity N2 we designed so, that it consists of two segments of *I-V* characteristics with NDR. Eigenvalues of singularity N2 in fig.4a, for parameters:

$R=0$, $L=1e\text{-}10$H, $C=2,6e\text{-}13$F (6)

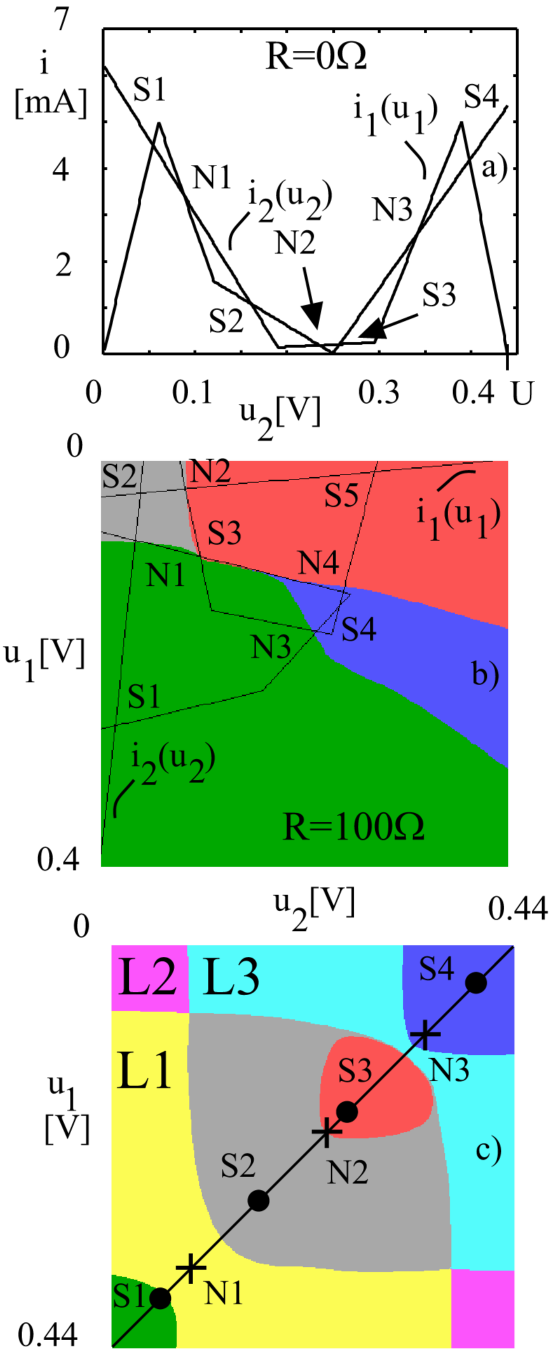

Figure 5 a) *I-V* characteristics in the projection into the i,u_2 plane at $R=0$, b) The projection of cross-sections of *I-V* areas into the plane u_1,u_2 at $R=100\Omega$, and cross-section of S3 for ${}^{S3}i=2,28$ mA. c) Cross-sections of BS in plane u_1,u_2 at $i=0$mA, $R=0$.

are listed in Table 2. As we can see, N2 is not a classic saddle singularity, because it has all their real parts of eigenvalues greater than 0. The others N1 and N3 in fig.4a) or fig.5a) are characterized by the same structure of eigenvalues.

Cross-sections of BS for $R=0$, parameters (6) and $i=0$ in the plane u_1,u_2 were done by the same algorithm mentioned in [1], [14], [15], like in the fig. 3. From these cross-sections are obvious regions of attractivity for particular attractors – stable singularities S1 ÷ S4 and undesirable SLC L1 ÷ L4.

Table 2 Eigenvalues for an unstable singularity N2

	N2
λ_1	4.615384615384615e+010
$\lambda_{2,3}$	2.307692307692307e+010 ± ±2.763883726649490e+011i

Regions of attractivity in fig. 4c) and fig. 5c) for stable singularities S1 ÷ S4 are indicated by placing the symbol (S1 ÷ S4) in the color field, whereas the symbol ● corresponds to the actual position of stable singularity in u_1,u_2 plane. The symbol + in the same figures denotes the actual positions of saddles N1 ÷ N3.

As can be seen from both figures, quaternary memory at $R=0$ is characterized not only by four regions of attractivity for S1 ÷ S4, but also by other regions of attractivity of undesirable SLC denoted L1 ÷ L4. Because the structure in fig.4a) is symmetrical, regions of attractivity in fig. 4c) are in the plane u_1,u_2 distributed symmetrically in comparison with fig.5a) and fig.5c). Interesting is also finding that in fig. 4c) are shown regions of attractivity for 4 SLC, but in fig. 5c) are only 3 SLC. Effect of change even only one segment of the *I-V* characteristic in this case is obvious.

If we choose $R=100\Omega$, so from fig.4b) and fig.5b) we can see that SLC ceased to exist and circuits have only a few areas of attractivity. In fig.4b) at $R=100\Omega$, the number of singularities did not increase. Increasing the number of singularities for $R>0$ therefore depends on properly designed *I-V* characteristics. Circuit in fig.4b) is no longer characterised by four, but only by three regions of attractivity for attractors S1, S2 and S4, because singularity S3 is again unstable, which confirms fig.4b), but also their eigenvalues from Matlab listed in Table 3. Thus from four-valued (quaternary) memory for $R=0$ we obtained for $R=100\Omega$ again only ternary memory.

Table 3 Eigenvalues for an unstable singularity S3

	S3
λ_1	2.196153846153846e+011
λ_2	1.528936382449410e+011
λ_3	-9.332782536295563e+011

A similar situation occurred also for the structure in fig.5. While at $R=0$ were in the circuit four attractors (S1 ÷ S4), at $R=100\Omega$ the number of singularities increased. If it would hold alternation of singularities stable - unstable - stable, etc., as at $R=0$, then at $R=100\Omega$ we would obtain even five stable singularities. But reality resulting from fig.5b) is quite different. Singularity S3 again becomes unstable, because it lies exactly on the boundary of three regions of attractivity. Number of stable singularities, namely S1, S2, S4 and S5, in this case remains unchanged. It is the same for $R=100\Omega$ and for $R=0$.

From both structures in fig.4 and fig.5 it is clear that when $R=100\Omega$, there was created singularity, which in terms of alternating singularities (stable – unstable) should be stable, but it was shown that, like in fig. 3, it is unstable singularity. Then, the final number of stable singularities is not greater than would appear based on conventional notions for $R=0$.

Conclusion. Based on mentioned findings we can conclude that if by influence of *R* tilting the *I-V* planes of the elements occurs so that there is not only the multiplication of singularities, but also to the fact that singularities are created by segments with negative differential resistance, then it will apply that:

• the number of unstable singularities will be greater than the number of stable singularities,

• it is not possible due to the impact of the loading plane *R* to expect changing singularities (stable - unstable) in terms of projections into the i,u_2 or i,u_1 plane, nor even from the perspective of the load plane.

In the case of utilization changes in the number of singularities in sequential circuits, the circuit should be subjected to exact analysis as it was also in the works [1], [4], [16], [17]. In terms of non-linear circuits and state space are not ruled out other interesting publication areas and topics of interest for international cooperation.

Acknowledgement

We support research activities in Slovakia / Project is co-financed from EU funds. This paper was developed within the Project "Centre of Excellence of the Integrated Research & Exploitation the Advanced Materials and Technologies in the Automotive Electronics ", ITMS 26220120055

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Стаття надійшла 06.06.2011 р.
Рекомендовано до друку к.т.н., доц. Кореньковою Т.В

ГРАНИЧНАЯ ПОВЕРХНОСТЬ И УРОВЕНЬ НАГРУЗКИ ТЕРНАРНОЙ ПАМЯТИ

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В статье показано воздействие уровня нагрузки r на характер сингулярностей многостабильной (многозначной) памяти. При r>0 в цепи с двумя последовательно соединенными резонансными туннельными диодами имеет место изменение числа сингулярностей. Таким образом, бинарная или многостабильная память может быть создана лишь за счет изменения r. Однако, эксперименты указывают, что увеличение общего числа сингулярностей в схеме не всегда означает увеличение числа устойчивых сингулярностей.

Ключевые слова: пространство состояний, уровень нагрузки, сингулярность, тернарная память, резонансный туннельный диод

ГРАНИЧНА ПОВЕРХНЯ І РІВЕНЬ НАВАНТАЖЕННЯ ТЕРНАРНОЇ ПАМ’ЯТІ

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У статті показано вплив рівня навантаження r на характер сингулярностей багатостабільної (багатозначної) пам'яті. При r> 0 в ланцюзі з двома послідовно з'єднаними резонансними тунельними діодами має місце зміна числа сингулярностей. Таким чином, бінарна або багатостабільна пам'ять може бути створена лише за рахунок зміни r. Однак, експерименти вказують, що збільшення загального числа сингулярностей у схемі не завжди означає збільшення числа стійких сингулярностей.

Ключові слова: простір станів, рівень навантаження, сингулярність, тернарна пам'ять, резонансний тунельний діод