CONSIDERATIONS UPON THE ANALOGY AMONG ELECTROTHERMAL PHENOMENA WITHIN FUSES AND THEIR SEMICONDUCTOR PROTECTION

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The present paper presents the electrothermal analogies between high-speed fuses and semiconductors, in joint operation. The thermal phenomena in rating mode and the electrical values that influence the heating of fuses and semiconductors are analyzed. In short-circuit mode equivalent thermal diagrams for fuses and semiconductors are presented and analogies and differences between them are established.

On the basis of the established analogies we present safe procedures of semiconductors with fuses.

1. INTRODUCTION

In order to protect the semiconductors with electrical fuses with fusibles, the electrothermal phenomena in high-speed fuses and in semiconductors should obey the same physical laws and the same qualitative and quantitative mathematical relations. In reality the things are not so, and that's why the electrothermal phenomena that appear in semiconductors and fuses must be thoroughly studied, and their functional parameters must be correlated.

On the basis of electrothermal analogies, we must establish exactely the correlations between electrothermal phenomena in high-speed fuses and semiconductors and depending on these correlations we must study first the possibility of influencing the electrothermal parameters of the fuses in accordance with those of the semiconductors; we must do this because fuses are cheaper than semiconductors. A further step would be the correlation of these parameters for all in operating conditions: steady - state, overlood - state and short-circuit state.

2. ELECTROTHERMAL PHENOMENA IN STEADY-STATE MODE

2.1. General heating equations.

The thermal phenomena in fuses could be studied on the basis of the differential heating equation, in its most general form, given by the relation [1] ; [2] :

$$\gamma c \frac{\partial \tau(x,t)}{\partial t} = \lambda \frac{\partial^2 \tau(x,t)}{\partial x^2} - \left[\frac{l_x}{A_x} K - \rho_0 \alpha_0 J^2(x,t)\right]\tau(x,t) + \rho_a J^2(x,t) \qquad (1)$$

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In case of semiconductors the differential heating equation has the form [3]:

$$\gamma c \frac{\partial \Theta(x,t)}{\partial t} - \lambda \frac{\partial^2 \Theta(x,t)}{\partial x^2} = p(x,t) = U_o\, j(x,t) + r\, j^2(x,t) \qquad (2)$$

where: γ - is the specific mass in $\frac{g}{cm^3}$; c - the specific heat in $\frac{Ws}{{}^{o}Cg}$

λ - thermal conductivity, in W/cm^2 ^{o}C; $\tau(x,t)$, $\Theta(x,t)$-over - temperature and temperature respectively, in ^{o}C; l_x- the fusible perimeter lenght or the fusible's isthmuse perimeter length, in cm;

A_x- area of the fusible cross- section or area of the fusible's isthmus cross-section, in cm^2.

ρ_a ρ_o - resistivity at ambiant temperature, at 0^{o}C, in Ω cm;

α_o - resistivity variation coefficient with temperature in $\frac{1}{{}^{o}C}$;

J(x,t) - current density, in A/cm^2; U_o-semiconductor threshold voltage, in V; r-semiconductor resistance, in Ω .

As it can be seen, in the differencial equation (2), we neglected the heat convection transfer, and this is justified by the little lenght of the semiconductor.

If we compare the two differential equations (1) and (2), we notice that in fuses and semiconductors nonstationary thermal phenomena are guverned by different equations.

2.2. Electrothermal phenomena in fuses.

The heating of fuses in steady - state mode, is given by the differential equation (1), in which - in case of a very exact analysis - we must consider all the terms. That's to say that we should also- consider the first form of the equation (1). The explanation of this fact would be, that in steady-state conditions, at alternating or intermittent current, the temperature varies evidently with time. As it was demonstrated in paper [4], at alternating current, overtemperature is also alternating and the heating alternating component amplitude, depends on the ratio between the fusible thermal time constant and the alternating current period, and it can be at limit, twice greater than the overtemperature from the direct current.

It is difficult to analize equation (1) in this paper, neither do we have the necessary space for such an analysis, and that's why we are going to analyze the current square value depending on time and the space coordonate (x) in accordance with the fuses utilization diagram and the isthmuses form.

At the basis of this simplification is the hypothesis that thermal phenomena in fuses are determined by the current square effective value.

In Fig. 1 different forms of current depending on time are presented and in Fig. 2 different forms of fusibles' isthmuses.

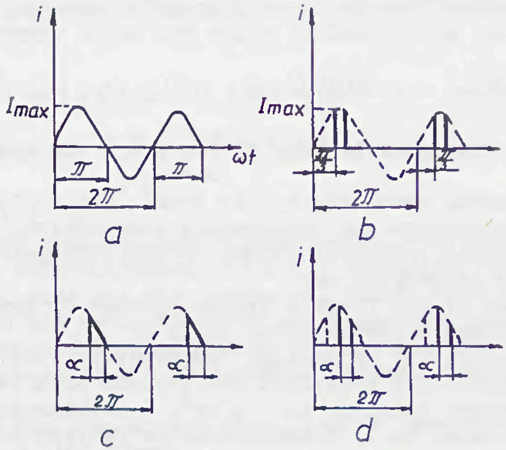


Fig.1 Forms of current depending on time

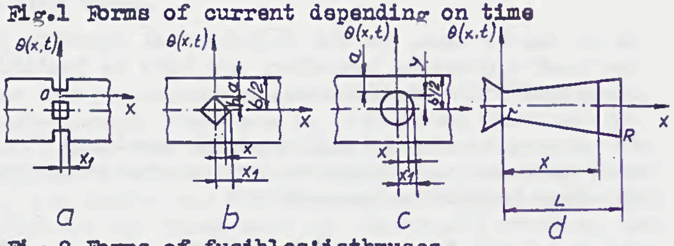


Fig.2 Forms of fusibles'isthmuses

Taking into account those mentioned above, the effective value of the electric current density for the fusibles'isthmuses (which must be introduced into equation (1) is given by the expression:

$$J(x,t) = \frac{I_{max}}{A(x)}\sqrt{\frac{1}{2\pi}\int_{\alpha_c}^{\alpha_b} f^2(\omega t)\, d(\omega t)} = \frac{I_{max}}{A(x)}K \qquad (3)$$

where: $f(\omega t)$ - current variation in time; T-alternating current period, in s; $A(x)$ - fusible's section area, in cm^2; α_c, α_b - angle of conduction and the thyristor blocking respectively.

Generally, $f(\omega t)$ has a sinusoidal form for resistive loads.

Considering relation (3) and Fig.1 and Fig.2, in Table 1, the current density values $J(x,t)$ depending on the electric current maximal value (I max.) for different angles of conduction of the electric current and different isthmus forms, are given.

Fusible heating can be calculated by means of the thermal effects superimposing method, which had been described in paper [1].

Table 1

Current density effective value J(x,t)

Form of isthmuses Figure 2 / Form of current Figure 1		Figure 2a	Figure 2b	Figure 2c	Figure 2d
Figure 1a	$\frac{KI_{max}}{A(x)}$	$\frac{0{,}707\,I_{max}}{gb}$	$\frac{0{,}707\,I_{max}}{2g\left[a+\frac{x}{x_1}\left(\frac{b}{2}-a\right)\right]}$	$\frac{0{,}707\,I_{max}}{2g\left(r+a-\sqrt{r^2-x^2}\right)}$	$\frac{0{,}707\,I_{max}}{\pi\left(r+\frac{R-r}{b}x\right)^2}$
Figure 1b	$\frac{KI_{max}}{A(x)}$	$\frac{0{,}39\,I_{max}}{gb}$	$\frac{0{,}39\,I_{max}}{2g\left[a+\frac{x}{x_1}\left(\frac{b}{2}-a\right)\right]}$	$\frac{0{,}39\,I_{max}}{2g\left(r+a-\sqrt{r^2-x^2}\right)}$	$\frac{0{,}39\,I_{max}}{\pi\left(r+\frac{R-r}{b}x\right)^2}$
Figure 1c	$\frac{KI_{max}}{A(x)}$	$\frac{I_{max}\sqrt{\frac{\alpha}{2\pi}+\frac{1}{8\pi}\sin 2(\pi-\alpha)}}{gb}$	$\frac{I_{max}\sqrt{\frac{\alpha}{2\pi}+\frac{1}{8\pi}\sin 2(\pi-\alpha)}}{2g\left[a+\frac{x}{x_1}\left(\frac{b}{2}-a\right)\right]}$	$\frac{I_{max}\sqrt{\frac{\alpha}{2\pi}+\frac{1}{8\pi}\sin 2(\pi-\alpha)}}{2g\left(r+a-\sqrt{r^2-x^2}\right)}$	$\frac{I_{max}\sqrt{\frac{\alpha}{2\pi}+\frac{1}{8\pi}\sin 2(\pi-\alpha)}}{\pi\left(r+\frac{R-r}{b}x\right)^2}$
Figure 1d	$\frac{KI_{max}}{A(x)}$	$\frac{*}{gb}$	$\frac{*}{2g\left[a+\frac{x}{x_1}\left(\frac{b}{2}-a\right)\right]}$	$\frac{*}{2g\left(r+a-\sqrt{r^2-a^2}\right)}$	$\frac{*}{\pi\left(r+\frac{R-r}{b}x\right)^2}$

$$* \quad I_{max}\sqrt{\frac{\alpha}{2\pi}-\frac{\sqrt{3}}{16\pi}-\frac{1}{8\pi}\sin 2\left(\frac{\pi}{3}+\alpha\right)}$$

2.3. Electrothermal phenomena in semiconductors. The analogies and differences between semiconductors and fuses are, roughly speaking, the following: in general, the fuses have long fusibles as compared with the semiconductors which are short; in semiconductors the electric current density to the space coordinates, at high frequencies is not constant; heating variation in semiconductor is important in the radial direction, too; l_x and A_x are constant in a semiconductor etc. The most important difference between semiconductors and fuses lies in the fact that whereas in fuses the thermal phenomena are determined by the alternating current effective value, in semiconductors the thermal phenomena - especially in steady - state mode - are determined by the alternating current effective and, especially, mean values. Considering the threshold voltage in the semiconductor, and accepting the hypothesis that U=f(I) characteristic is a straight-line, the dissipated power in a semiconductor is given by relation (5)

$$p(t) = U_0\, i(t) + r i^2(t) \tag{4}$$

from which we obtain the mean power in a period of time, under the form:

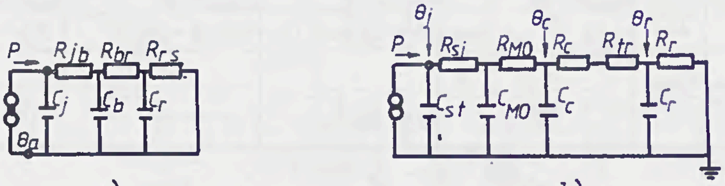
$$P = \frac{1}{T}\int_0^T p(t)\,dt = \frac{1}{T}\int_0^T U_0\, i(t)\,dt + \frac{r}{T}\int_0^T i^2\,dt = U_0 I_{med} + r I_{ef}^2 \tag{5}$$

Since the effective current determines the heating in steady-state mode for fuses, and the mean current in semiconductors (at a rate of 80 %), we consider necessary to show that there is a great difference between the effective and mean currents from the same branch of a rectifier circuit, thus, in a branch of a three-phase diagram with double alternance, for a commutation of 60 electric degrees, $I_{ef} = 1.73\, I_{mean}$, and this ratio increases very much for little angles of commutation [1].

3. EQUIVALENT THERMAL DIAGRAMS

On the basis of electrothermal analogies, equivalent thermal diagram with limited parameters (for semiconductors) were elaborated, diagrams that had been presented in literature [5] , [6]. In the present paper we shall also delimate, on the same principles, an equivalent thermal diagram for fuses.

3.1. **Semiconductor equivalent thermal diagram.** In Fig. 3 equivalent thermal diagrams for diodes (fig.3.a) and for thyristors (fig.3.b) are presented:



a) b)

Fig. 3 Semiconductor equivalent thermal diagrams

Thermal resistance is given by relation 6 ;

$$R_t = \frac{\Delta\theta}{p} = \frac{1}{\lambda}\int\frac{dl}{A} \qquad \left[\frac{^\circ C}{W}\right] \tag{6}$$

Thermal capacity is given by relation:

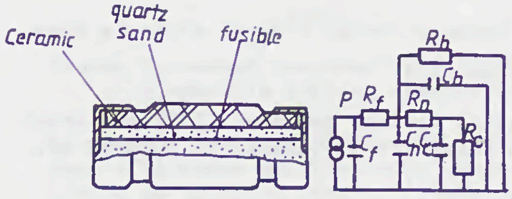
$$C_t = \frac{\int p\,dt}{\Delta\theta} = cM \qquad \left[\frac{Ws}{^\circ C}\right] \tag{7}$$

Thermal time constant results form relation:

$$\tau_t = R_t \cdot C_t \qquad [\,s\,] \tag{8}$$

The thermal diagrams from Fig. 3 can be solved by means of analogy with an electrical circuit. The values in Fig. 3 have the following significance; p - power developed in semiconductor; C_j; C_b and C_r - jonction, basis and radiator thermal capacities, in Ws/°C; R_{jb}; R_{br}; R_{rs} - thermal resistances between jonction - basis, basis-radiator and radiator - environment, in °C/W. The parameters for the thyristor thermal equivalent diagram are established in the same way.

3.2. **Fuse equivalent thermal diagram.** The simplest equivalent thermal diagram of a tube fuse, can be elaborated, considering the constructive type of the respective fuse. Thus, in Fig. 4 a tube fuse with a simple fusible, is presented



a) b)

Fig.4 Fuses with fusibles

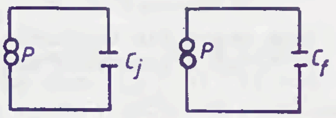


Fig.5 Equivalent thermal diagrams in short - circuit mode

In Fig. 4.b the thermal equivalent diagram of such a fuse is presented. R and C represent the thermal resistances and the thermal capacities respectively of: fusible (R_f, C_f) quartz sand (R_n, C_n), ceramic body (R_o, C_o) and jonction pole (R_b; C_b).

4. ELECTROTHERMAL PHENOMENA IN SHORT-CIRCUIT MODE

4.1. Semiconductor sofe procedures. The condition of semiconductor protection with fuses against short-circuit is satisfied if between (I^2t) admitted by the semiconductor and total (I^2t) of the fuse is observed the relation:

$$(I^2t)\ \text{semiconductor} < \text{total}\ (I^2t)\ \text{fuse} \tag{9}$$

When connecting in parallel identical semiconductors with individual protection fuses of the same type, it is also necessary to observe the condition of selectivity. That means that in case of semiconductor malfunction, the fuse on the respective branch melts and breaks the short-circuit current before the fuses on the complementary branch melt too. This condition is satisfied if the pre-arch (I^2t) of n fuses from the complementary branch is grater than the total (I^2t) of the defect fuse.

The pre-arch (I^2t) value, produced by the $\frac{c}{n}$ i current in any of the n fuses on the complementary branch is:

$$(I^2t)_{prearch} = \int_0^{tp} \left(\frac{c}{n}\, i\right)^2 dt = \frac{c^2}{n^2}\int_0^{tp} i^2 dt \tag{10}$$

where: c is a fuse loading factor.

Total (I^2t) value of a fuse on the defect branch is:

$$\text{total}\ (I^2t)\ \text{of fuse} = \int_0^{\infty} i^2\, dt \tag{11}$$

The pre-arch (I^2t) value of the n fuses on the complementary branch is given by the relation:

$$\text{total pre-arch}(I^2t) = \text{pre-arch}\ n^2(I^2t)\ \text{of the n fuse} \tag{12}$$

So, the selectivity condition is satisfied if :

Total pre-arch (I^2t) of the n fuses $>$ total (^2t) of a single fuse

$\Longrightarrow$ pre-arch $n^2(I^2t) >$ total (I^2t)

From where the connecting relation between pre-arch (I^2t) and total (I^2t) of a fuse that assures a selective protection is infered by:

$$n^2 > \frac{\text{total}\,(I^2t)}{\text{pre-arch}(I^2t)} \qquad (13)$$

Considering relation (13), the ratio between total (I^2t) and pre - arch (I^2t) of a fuse with selective protection, used with 2 thyristors connected in parallel, must be less than 4; for 3 fuses in parallel it must be less than 9 and for 4 fuses in parallel it must be less than 16.

We underline the fact that the ratio presented in relation (13) is less than 4, and that it is difficult to be obtained in case of high-speed fuses. The fuses produced by firms such as Siemens, LK-NES or Soviet firms etc. have this ratio between 5 and 11. From what we know, only the Romanian high-speed fuses and those produced by Ferraz have this ratio less than 3. It results that two thyristors functioning in parallel can be selectively protected only with these fuses.

4.2. **Individual protection analyzed on the basis of equivalent thermal diagrams.** For very short periods, while the short-circuit lasts and when the heat transfer can be neglected, the equivalent thermal diagram from Fig.3 and Fig. 4 can be simplified as in Fig.5. Considering the analogies mentioned above, the following relation between overtemperature and energies developed in fuses and semiconductors, are obtained:

In semiconductor we obtain:

$$\tau_j = \frac{1}{C_j}\int p\,dt \qquad (14)$$

and in fuse:

$$\tau_f = \frac{1}{C_f}\int p\,dt \qquad (15)$$

At short-circuit, we can consider that the whole energy developed in a semiconductor is stored by the capacity C_j, and then, considering the expression (4) we obtain the relation:

$$E_s = \int_0^t p\,dt = U_0\int_0^t i\,dt + r\int_0^t i^2 dt = C_j\tau_j \qquad (16)$$

By analogy, the energy developed in the fuses'fusibles is obtained in:

$$E_f = \int_0^{tp} p\,dt = r_f \int_0^{tp} i^2 dt = C_f\,(\theta_t - \theta_a) \qquad (17)$$

where: E_f-energy necessary for fusible melting; t_p-pre-arch time;
θ_t-fusible melting temperature; θ_a-ambiant temperature

In case of semiconductors - for very short periods - which is the case of intense short-circuit currents- the term $U_0 \int i\,dt$ is very little as compared with $r \int i^2 dt$ and in these conditions relations (16) can be written:

$$I^2 t = \int_0^{t} i^2\,dt = \frac{C_j}{r}\,\tau_j \qquad (18)$$

So, total (I^2t) produced by the short-circuit, in a period t is directly proportional with the jonction thermal capacity and invers proportional with its resistance.

In the same way, the highest the jonction temperature is the highest (I^2t) is. Generally this temperature is not higher than 140°C.

In case of fuses, from relation (17) we obtain:

$$\left(I^2 t\right)_{prearch} = \int_0^{tp} i^2\,dt = \frac{C_f}{r_f}\,(\theta_t - \theta_a) \qquad (19)$$

Comparing relations 18 and 19, we notice that thermal effects in semiconductors and fuses, at short-circuit, are relatively analogous if we take into consideration total (I^2t) for semiconductors, and pre-arch (I^2t) for fuses. But as we have already demonstrated, pre-arch (I^2t) in fuses represents only a little part from the total (I^2t). The most serious drawback is the fact that in case of fuses there is no well determined relation between pre-arch (I^2t) and total(I^2t).

Consequently, in case of fuses, pre-arch (I^2t) and total (I^2t) vary depending on many factors. Out of these factors we could mention: type of fusible; electric circuit parameters; moment of apparition of the electric arch; power - supply voltage evolution during the electric arch etc.

However, we determine in case of fuses a maximum arch(I^2t) for the same voltage value. But since the arch (I^2t) is for some types of fuses about 9 times grater than the pre-arch value, we can't use relation (19) with the same exactity as relation (18).

There is another big difference between the behavious of fuses and semiconductors in case of short-circuit. These differences are even more obvious, if we analyze comparative by the parameters presented in Tabel 2 for fuses and semiconductors and the physical constants of materials used for fuses and semiconductors, presented in Table 3.

Table 2

Some fuses and semiconductors parameters

Parameter	The isthmuses of the fusible	Semiconductor	
		The jonction of the diode	The jonction of the thiristor
Generated specific power $\left[\frac{W}{cm^3}\right]$	360	10	10
Steady state temperature $[^\circ C]$	300 ÷ 400	190	150
Thermal resistance $\left[\frac{^\circ C}{W}\right]$	10	0.13 ÷ 3	1
Thermal capacitie $\left[\frac{J}{^\circ C}\right]$	203	—	735

Table 3

Physical constants of materials used for fuses and semiconductors

Constants of materials / Material	Specific heat capacity 20°C $[J/g^\circ C]$ $c \cdot 10^{-3}$	Thermal conductivity $\lambda\,[W/cm \cdot {}^\circ C]\ 10^{-2}$	Diffusivity $a=\frac{\lambda}{\gamma c}\cdot 10^{-6}$ $[m^2/s]$
SILVER	230	418	171
ALUMINIUM	920	204	81
TIN	235	64	37.8
COPPER	393	380	108
MOLYBDENUM	270	145	53
SILICON	735	84	49
WOLFRAM	141	130	61

5. CONCLUSIONS

The above analysis demonstrated certain analogies and differences between the electrothermal phenomena in fuses and semiconductors.

The analogies consist in the fact that both the fuses and semiconductors under go the electric current heating.

In steady- state mode, the difference lies in the fact that in base of fuses only the effective current is the cause of heating where as in case of semiconductors, the heating is determined by both the current effective value and - especially - by the current mean value R_t and C_t parameters and the volumetric power differ very much from fuses to semiconductors the thermal time constant of fusibles'isthmuses are very close as values to the semiconductor jonction time constant.

At short-circuit, (I^2t) produced by the short-circuit current determines the heating of the semiconductor, but in case of fuses, the pre-arch (I^2t) leads to the melting of the fuse, and the total(I^2t) assures the semiconductor protection.

In case of fuses, pre-arch (I^2t) and total (I^2t) differ very much. The physical constants of materials used in fuses (Ag) and of materials used for semiconductor jonction (Mb, Si etc.) differ very much too.

Despite the differences between the thermoelectrical parameters of fuses and semiconductors, we can choose a coresponding safe procedure and corralation between them.

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