MODELLING OF SEMICONDUCTOR FUSES IN EMTP

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Abstract

This paper describes a physical model to simulate three dimensional transient thermal responses of semiconductor fuses stimulated by electric current. The work is motivated due to the increasing demands of reliable protection of semiconductor devices and the lifetime prediction for fuses. Thermal behaviour of fuses has been simulated in EMTP (Electro-Magnetic Transient Program) by using the thermal electrical analogue method. For current pulses with different I^2t values, corresponding lifetimes of fuses were predicted according to thermal fatigue. The validity of the thermal model was checked by comparison of the resulting melting characteristic with the manufacture curve. The thermal model finally resulted in lifetime determinations which were confirmed by experiments.

Keyword

Network, fuse, transients, heat transfer, semiconductor

List of principal symbols

A	cross sectional area
b	fatigue strength exponent -0.08
c	specific heat
C_{th}	thermal capacitor
E	modulus of elasticity $71*10^3$ MPa
I	current
I_s	injected current for coupled network
i	electric current
j	current density
l	length
N	number of current pulses to blowing
R_{el}	electrical resistance
R_{th}	thermal resistance
t	time
T	temperature
α	diffusion coefficient
β	thermal expansion coefficient $19.68*10^{-6}$
δ	diffusion depth; deflection factor
λ	thermal conductivity
ρ	resistivity
ϕ	electric potential
γ	mass density
σ'_f	fatigue stress coefficient 130 MP_a
Δx	length of a subvolume along the x axis
Δy	length of a subvolume along the y axis
Δz	length of a subvolume along the z axis
$\Delta\varepsilon_e$	elastic strain
$\Delta\varepsilon_{th}$	thermal strain

1. INTRODUCTION

Electric fuses usually consist of metal fuse elements, end caps, contacts and a cartridge. Figure 1 shows a typical fuse configuration for semiconductor fuses.

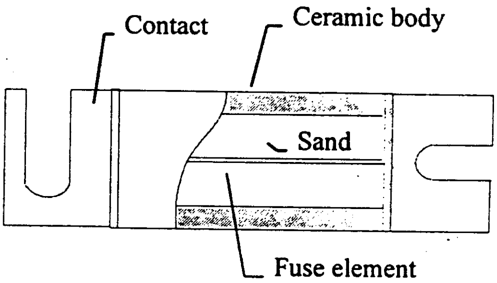

Figure 1 Typical semiconductor protection fuse

The fuse element consists of a metal strip with some rows of notches (Fig. 2), which is surrounded by sand in a ceramic cartridge. In case of a circuit fault, arcs are initiated at the notches and later the fault is interrupted so to secure the circuit and equipment.

One of the most important fuse characteristics is the current - time characteristic, so called *I-t* characteristic. As fuses are submitted to cyclic currents, *I-t* characteristics will shift due to thermal fatigue caused by temperature variations, this may lead to malfunction. Therefore there is a need to study fuse lifetimes. For this reason, thermal behaviour of fuses should be understood.

During the last 20 years, several calculating methods have been proposed to simulate fuse current-time characteristics, such as different methods like the finite difference method, the finite element method and the network analogue method.

It has been demonstrated that thermal problem can be modelled by its electrical equivalents. Among many advantages, components in the networks have clear physical meaning. The convergence of numerical solution is guaranteed because of existence of components and their physical behaviour. Application of the model to other constructions can easily be realised.

EMTP has been widely used for simulating electrical transients in networks. In this work, EMTP as a tool is chosen to find the solution of the three dimensional thermal problems according to their electrical equivalents. Additionally, students in power engineering can get the knowledge of EMTP for huge electrical network simulations.

The primary objective of the fuse reliability project is to understand fuse ageing mechanisms and to provide application guidance for industries. However this article will limit attempts to simulate thermal responses of fuses excited by currents and provide lifetime predictions.

2. PHYSICAL MODELS

2.1. Geometry of the fuse element

Commercial power fuses are taken as simulation objects. Fuses are rated for 160 A and 660 V. The maximum breaking capacity is 120 kA. Figure 2 shows the element geometry. Element dimensions are in millimetre.

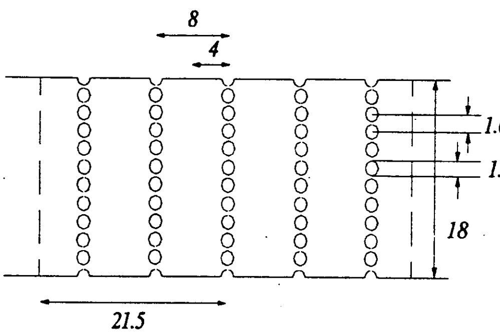

Figure 2 Element geometry

The fuse element made of silver without M-spots consists of five rows of notches and each row has 10 holes. The hole has a diameter of 1.5 mm. The overall element size is 43mm*18mm*0.135mm.

The fuse element is surrounded by sand with an average grain size diameter of 0.36 mm. The sand packing density is about 1.79 g/cm^3. The thickness of the surrounding ceramic body is about 5 mm. The distance between the body and the element is about 9 mm.

2.2. Thermal behaviour of fuses

In order to find the temperature distribution, two equations should be solved.

$$\nabla\nabla\phi = 0 \qquad (2\text{-}1)$$

$$\gamma c \frac{\partial T}{\partial t} = \nabla\lambda\nabla T + \rho j^2 \qquad (2\text{-}2)$$

The first is the field equation, which describes the electric potential distribution. The second is the energy balance equation. It states that the input energy due to joule heating is balanced by the heat conduction and the energy to raise the temperature of the object. The boundary conditions are specified as

$$T = T_0 = 20\ °\mathrm{C}$$

$$\phi = \phi_0 = 0$$

$$\phi = \phi_1$$

ϕ_1 is a known constant at one boundary.

Regarding fuse ageing and thermal behaviour, simulations for both long time and short time current conduction are required. To get an insight of heat transfer, it is easy to start with the idea of thermal diffusion depth (or the penetration depth). This concepts states that the distance depends on heat conducting time and thermal diffusion coefficient. An approximation of the diffusion depth [1] is given by

$$\delta(t) = \sqrt{12\alpha t} \qquad (2\text{-}3)$$

The diffusion coefficient is given by

$$\alpha = \frac{\lambda}{\gamma c} \qquad (2\text{-}4)$$

To understand the heat transfer process in the fuse, the middle row of the notch is considered only, because it has the highest temperature as electric current flows.

Using the fuse element dimensions and the expression of diffusion depth, the following time limits are established. For times less than 0.3 ms, heat conduction is limited within the notch zone (0.75mm), hence adiabatic heating is suggested. Diffusion depth is about 4 mm in the silver element for 9 ms. Diffusion depth in sand is equal to the thickness of the element (0.135 mm) for 7 ms. These two time limits give an impression of the adiabatic heating. After about 150 ms, diffusion depth reaches 4 mm in sand. From 150 ms to 300 ms heat conduction in the element and sand have the common influence. After about 300 ms, heat conduction from the central notch reaches the end contacts. Heat transferred to contacts can not be neglected. After about 30 seconds, heat conduction reaches the ceramic body. Therefore in this range contacts and sand are heat transfer media. Heat convection and radiation of the ceramic body take place. As a consequence, all possible heat transfer factors should be considered above this time limit.

Within 300 ms, heat energy conducts in the silver element and sand. There is no heat conduction in the ceramic body for this period. Figure 3.1 shows relevant dimensions for this simulation. Because of geometric symmetry, only a small region of the element is required to be simulated [2]. Above 300 ms, to simplify the simulation, the contact temperature and the outer surface temperature of the ceramic body are assumed to be the same as the surrounding temperature. Figure 3.2 shows the simulation region of the fuse element.

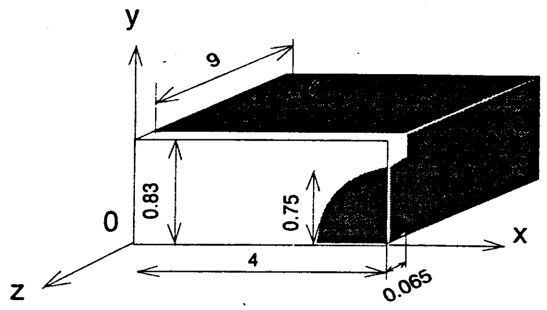

Figure 3.1 Simulation region for times shorter than 300 ms

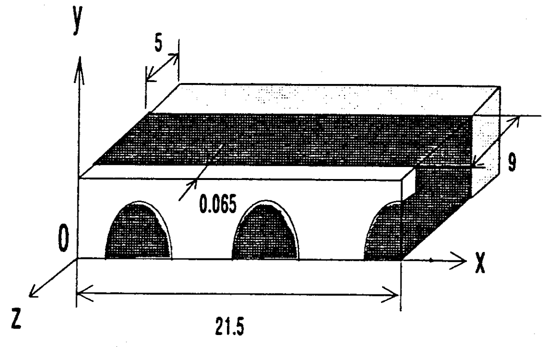

Figure 3.2 Simulation region for times between 300 ms and 30 s

2.3. Electrical equivalents

Electrical equivalents are network components transformed from the thermal and electrical problems. Their quantities are defined according to Eqs. 2.1 and 2.2. The simulation region is divided into subvolumes. In one dimension, each subvolume behaves like a lumped component. Physical parameters of components are determined by the problem to solve and the physical properties of the simulation region. R_{el} is an electrical resistance. R_{th} is a thermal resistance. C_{th} is a capacitor and $i(t)$ is a current source. They are defined as

$$R_{el} = \rho \frac{l}{A} \qquad (2\text{-}5)$$

$$R_{th} = \frac{l}{\lambda A} \qquad (2\text{-}6)$$

$$C_{th} = c\gamma\, l\, A \qquad (2\text{-}7)$$

$$I = i^2(t) R_{el} \qquad (2\text{-}8)$$

2.4. Lifetime predictions

The prime objective of the reliability study is to relate the fuse lifetimes with the load current. Based on the relationship between the stress and the strain in the elastic range, the number of current pulses N which fuses can withstand may be predicted [4,5] according to

$$\frac{\Delta\varepsilon_e}{2} E = \sigma_{f'} N^b \qquad (2\text{-}9)$$

Thermal strain induced in the notch region of the fuse element due to a current pulse is proportional to the temperature rise. The total thermal strain can be obtained by integrating from x= l_1 to l_2 and is approximated by

$$\Delta\varepsilon_{th} = \sum_{x=l_1}^{l_2} \beta\, T(x) = A_0 \beta\, T_{\max} \qquad (2\text{-}10)$$

where A_0, l_1, and l_2 are constants. The mechanical strain is simply to take the form

$$\Delta\varepsilon_e = \delta\, \Delta\varepsilon_{th} \qquad (2\text{-}11)$$

where δ is the deflection factor $(0.7 \sim 0.95)$.

3. NETWORK REPRESENTATION

Previous section has discussed general forms of component determination. In this section, sub circuits corresponding to subvolumes will be represented.

3.1. Sub-volume generation

To achieve high resolution, small subvolumes are necessary. That means in the later stage, the complete network will be very large. Because of computer memory, the amount of network components is limited. Subvolumes with different size are chosen to compensate this limitation. Figure 4 shows a typical subvolume and its dimensions.

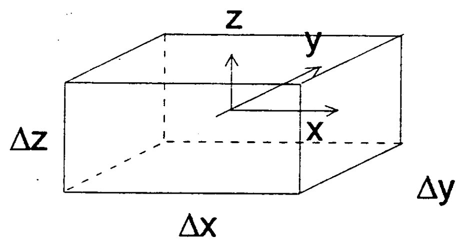

Figure 4 Co-ordinates and subvolume dimensions

3.2. Sub circuits

Corresponding to Fig. 3.1 and 3.2, the area for the electric current flow simulation in the silver can be divided into small sub-volumes. For a subvolume, electrical behaviour is represented by four resistances.

$$R_{el}1 = R_{el}3 = \rho \frac{\Delta x}{2\Delta y \Delta z} \qquad (3\text{-}1)$$

$$R_{el}2 = R_{el}4 = \rho \frac{\Delta y}{2\,\Delta x \Delta z} \qquad (3\text{-}2)$$

A two dimensional representation is adequate here because of small thickness of the metal strip. The corresponding subcircuit is represented in Fig. 5.

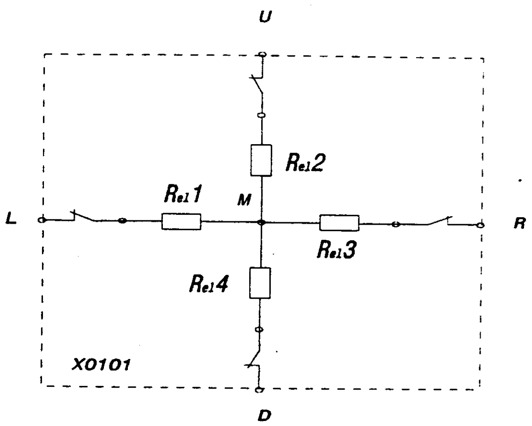

Figure 5 Subcircuit for electric current flow

The resistance values are determined by subvolume dimensions and its resistivity. The length is from the centre point of the subvolume to the boundary surface. It is assumed that the current direction is perpendicular upon the relevant cross section. The resistivity of silver is dependent on the temperature of the subvolume.

For heat transfer, three dimensional modelling is necessary. Heat conduction is represented by six equivalent resistances. Resistance values depend on the thermal conduction coefficient. Energy due to electrical current flow is represented by injecting an equivalent thermal current. Energy used to increase the subvolume temperature is represented by charging an equivalent capacitor. Figure 6 shows the equivalent subcircuit for thermal simulation.

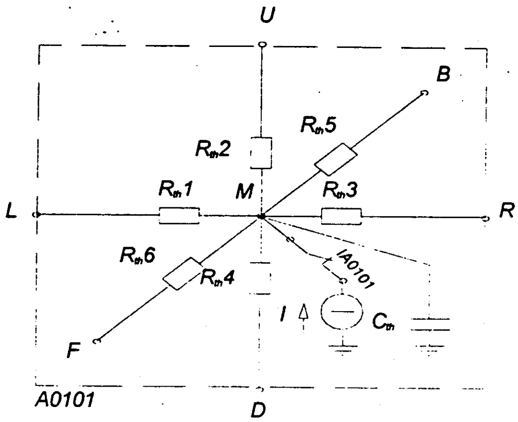

Figure 6 Equivalent subcircuit of heat conduction

Component parameters are defined as

$$R_{th}1 = R_{th}3 = \frac{\Delta x}{\lambda\, 2\, \Delta y \Delta z} \qquad (3\text{-}3)$$

$$R_{th}2 = R_{th}4 = \frac{\Delta z}{\lambda\, 2\, \Delta y \Delta x} \qquad (3\text{-}4)$$

$$R_{th}5 = R_{th}6 = \frac{\Delta y}{\lambda\, 2\, \Delta z \Delta x} \qquad (3\text{-}5)$$

$$C_{th} = c\gamma\ \Delta x \Delta y \Delta z \qquad (3\text{-}6)$$

$$I = i_1^2\, R_{el}1 + i_2^2\, R_{el}2 + i_3^2\, R_{el}3 + i_4^2\, R_{el}4 \qquad (3\text{-}7)$$

Component parameters for the sand and the ceramic body can be obtained in a similar way. Of course, no branches exist in the subcircuit for the electric current flow in sand. The complete circuit consists of all sub circuits. From this circuit, temperature values at different nodes are obtained.

For decoupled solutions, current distribution and temperature distribution are obtained separately. However, for the coupled solutions, two networks have to be solved simultaneously. In the subcircuit for simulating current flow, the temperature dependent resistance is represented as a current source and a constant resistance together. Consequently, the subcircuit shown in Fig. 7 is used to simulate the electric current flow. Figure 8 presents the coupled subcircuit for the heat transfer in the silver strip (see Fig. 7).

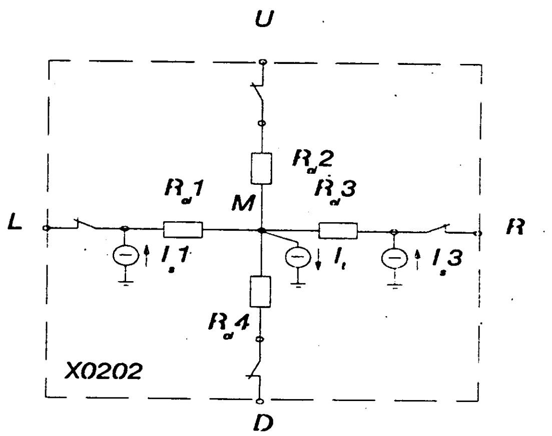

Figure 7 Subcircuit for electric current flow including temperature dependence

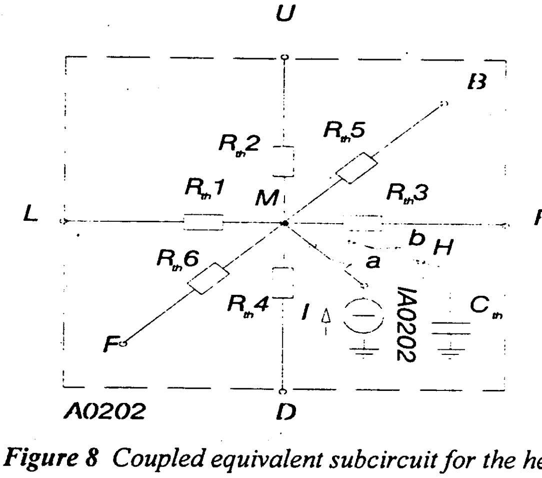

Figure 8 Coupled equivalent subcircuit for the heat conduction in the silver strip (see Fig. 7)

To solve the complete network, an iteration procedure has to be applied. This is shown in Fig. 9, where *T* is an period for the coupled network simulation. The process is realised by exerting two triggering signals to switches *a* and switch *b*.

First, two switches are closed by trigger 1. Temperature values at all nodes are calculated. The temperature of the silver strip is measured by the measuring switch b in one time step. These two switches are opened by trigger 2. Consequently, temperatures at all nodes are hold. New electric current distribution is calculated during two time steps because of nonlinearity.

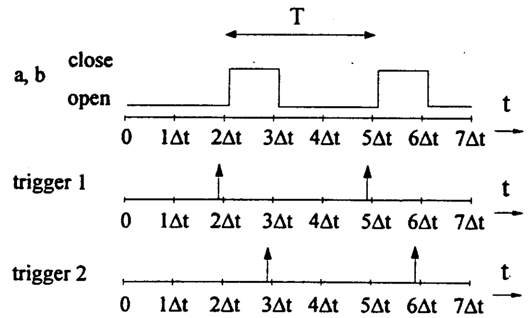

***Figure 9** Iteration scheme for the coupled non-linear network*

As the stable state is reached, two switches are closed again and then temperatures at the next instant can be calculated.

3.3. Boundary conditions

In the simulation, the last sand layer and the network nodes at the end contact are connected to the thermal network ground. The temperature of the layer is at a room temperature. Heat conduction through the narrow edges of the silver strip into sand is assumed to be neglected.

3.4. Data input and output files

For a big network, to generate data input files for EMTP by hands is a tedious task and often difficult. For this reason, a program (SEMIFUSE.PAS) is developed to form an input data file for EMTP (EMTP.INP). All resistances, capacitors, switches, current sources and TACS (Transient Analysis of Control Systems) are connected according to the subvolume representation. Calculation results in EMTP can be stored in the ASCII format. From these files, two dimensional and three dimensional plots can be produced.

4. RESULTS AND DISCUSSION

To estimate the damage done to the fuse element, the temperature variations have to be calculated. Figure 10 shows a typical temperature distribution near the notch (the maximum temperature 574 °C) at the time instant of 7 ms during a current pulse with the effective current 1250 A for 10 ms. This graph indicates the most heated location is around the notch within about 1 mm for the time period of 7 ms.

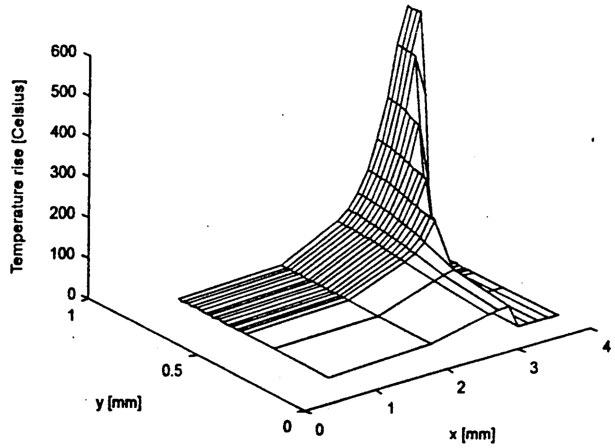

***Figure 10** Three dimensional temperature distribution at 7ms for a 10 ms current pulse of 1250 A*

Figure 11 shows simulation results of the maximum temperature rise for a current pulse of 700 A. The current indicated in the graph is 1/44 value of the total current through the fuse element. The graph indicates the simulated temperature profile as a function of time. After the current flows, the temperature rises up with a time delay. The maximum temperature of the element is reached after the current peak, the temperature delays about 2 ms. As the current decreases, the temperature falls down.

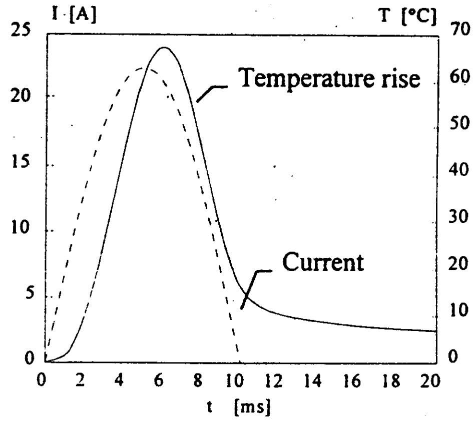

***Figure 11** Simulation for current pulses*

To examine the current - time (I-t) characteristics in the long time range, measurements of melting times for 300 A, 400 A and 600 A were performed. The minimum fusing current from the simulation was found to be 205 A. Comparison of manufacturer *I-t* characteristic, the measurements and calculated results from EMTP is made in Fig. 12. This graph shows that measured values ("♦") are slightly below the manufacture curve and the simulated results. In general, it can also be seen that calculations are in agreement with both results from the fuse manufacturer and the measurements.

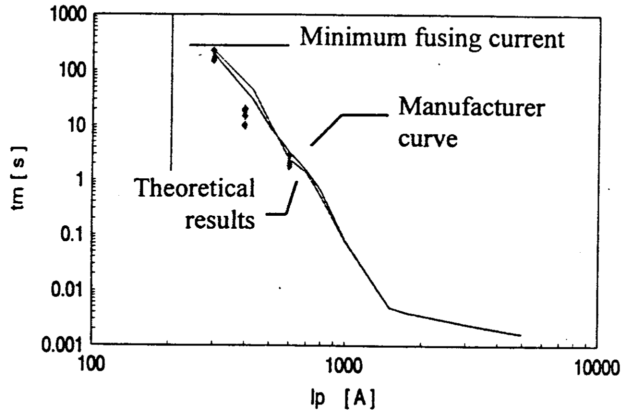

Figure 12 Comparison of theoretical results with manufacturer curve and measurements "♦"

To study the deformation mechanism, lifetime tests were performed with different shapes of fuse elements (A and C). After pulsed currents were applied to the tested objects, from the experiments numbers of current pulses which fuses withstood and their mean values were obtained. Lifetime predictions for commercial fuses were made by using the method in Section 2.4. Parameters A_0, l_1, , l_2 and δ were determined from the elements with one row of notches, which were found to be A_0 = 0.23, l_1, = 1.5 mm, l_2 = 4 mm and δ = 0.88 [4]. Comparisons of predictions and the mean values of observations are shown in Fig. 13.

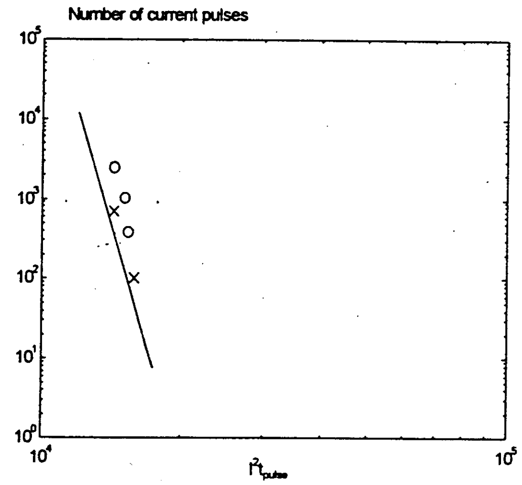

Figure 13 Comparisons of predictions and observations

"x" : type A; "o" : type C

This figure clearly shows that for pulsed currents with a duration of 10 ms, lifetimes of fuses with sand decrease as the I^2t value increases, predictions are in the conservative side of the number of current pulses which fuses withstand.

In the theoretical analysis, for lifetime predictions the material properties were from the literature [5]. Resistivity as a function of temperature, thermal conductivity, specific heat and mass density of silver were taken from the literature [3]. For sand and ceramic, the commonly used values were introduced. Some properties are given in Table 1.

***Table 1** Material properties in the simulation*

	λ [W/mK]	γ [kg/m³]	c [J/kgK]
silver	391	10492	276
sand	0.3	1670	800
ceramic	1.46	2200	670

5. CONCLUSIONS

The proposed analogue method is proved to be a powerful tool for simulating thermal transient responses. EMTP numerical results of current - time characteristics of fuses show reasonable agreement with both manufacturer curve and measurements. From the calculated temperature rise, lifetime of fuses has been made and found to be in the conservative side of experimental observations.

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