TLM MODELLING OF THIN FILM FUSES ON SILICA AND ALUMINA

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ABSTRACT

Thin film electric fuses comprising of a metal layer bonded to an electrically insulating substrate such as silica or alumina have distinct advantages over conventional types. The element is in intimate contact with its support which provides an efficient sink for heat dissipated during quiescent operation. However the temperature dependence of the thermal time constants of alumina and silica are radically different; the former increases with increasing temperature while the latter decreases. This gives rise to a thermal feedback effect which is perhaps the most significant factor in determining pre-arcing performance in this type of device.

In this paper a novel numerical technique, three dimensional transmission line matrix (TLM), is used to predict the pre-arcing behaviour of thin film electric fuses on silica and alumina substrates. The results indicate that there is a complex interaction between the temperature dependence of the conductor resistance and the substrate thermal parameters (specific heat and thermal conductivity) which has important consequences for fast power semiconductor protection fuses.

INTRODUCTION

The development of new types of very fast power semiconductors has created considerable problems in terms of protection. Many of these devices can fail in times which are short compared to the pre-arcing time of conventional sand filled electric fuses. An alternative and potentially faster fuse can be constructed by depositing a very thin film of conducting metal on an electrically insulating substrate. In addition to providing mechanical support for the conductor, the substrate also acts as a heat sinking component during quiescent operation. The thermal behaviour of thin film fuses on insulating substrates has been examined experimentally and the results were reported at a previous ICEFA Conference[1]. It has been shown[2] that the properties of thin film fuses are dominated by the thermal properties of the substrate.

The effort involved in performance optimisation can be significantly reduced by means of device modelling. The time and space variation of parameters such as temperature can be described by means of a suitable differential equation. However for a given set of boundary conditions an analytic solution is not always possible and this is particularly true if one attempts to include the temperature dependence of parameters such as substrate specific heat and thermal conductivity or conductor resistivity.

The advent of digital computers has stimulated the use of numerical methods of solution. The numerical solution of equations which are functions of space and time generally involves two discretisation steps i.e. one for each variable. The discretisation of space into nodes is simple enough but the subsequent time discretisation can, as in the case of the heat flow equation, lead to instabilities unless special precautions are taken.[3] In this paper a relatively novel technique, the transmission line matrix (TLM) method, is used to solve the three dimensional non-linear thermal diffusion equation for a thin film fuse.

THE TLM METHOD

The use of electrical analogies for the solution of differential equations is well accepted and the transmission line matrix (TLM) technique represents a new development in this area. It arises from the fact that any transmission line has capacitance (C_d), inductance (L_d) and resistance (R_d) distributed along its length. It can be shown that Maxwell's equations for propagation along a lossy transmission line can be expressed in one dimension as[4]:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = L_d C_d \frac{\partial^2 T}{\partial t^2} + R_d C_d \frac{\partial T}{\partial t} \qquad \ldots (1)$$

This describes the propagation of a wave which becomes attenuated. The first term represents lossless wave motion. A spike impulse launched into a transmission line will take a definite time to travel along the line. Thus if a physical problem can be modelled by an electrical network consisting of a matrix of transmission lines, then a solution of the network will provide a solution to the problem without the necessity of a separate time discretisation step. The TLM technique involves a discretisation of the problem space. Each spatial node is replaced by transmission line components in an analogous electrical network. Current or voltage impulses are injected into the network. During their progress through the network they obey Maxwell's equations. Thus the population of impulses as a function of time and position provides a solution to equation 1.

Under circumstances where a lossy transmission line fulfills the condition that $R_d C_d \ll$ (impulse velocity)$^{-2}$ then equation 1 reduces to an analogue of the heat flow equation. This forms the basis of the TLM method of thermal modelling. Figure 1 shows a three dimensional node together with a one dimensional lumped equivalent circuit. Any physical problem is modelled using a matrix of these nodes. Heat is input as impulse analogues at appropriate parts of the matrix. An iteration commences with a scattering of impulses. They travel along the lines and experience reflections if the impedances of adjacent nodes are unequal. At the end of a period Δt all impulses arrive at their new positions. The temperature rise at a particular node is then the sum of all incident impulses at that location. The process ends with an adjustment of the thermal capacitance, line impedance and thermal resistance (all functions of temperature) at each node in preparation for the next step.

Boundaries can be treated in the following ways:

(i) The terminating impedance is infinite (an electrical open circuit). In this case any impulse encountering the termination will be reflected back along the line with its phase unaltered.

(ii) The terminating impedance is zero (an electrical short circuit). In this case any impulse encountering the termination will be reflected with the opposite phase.

(iii) The terminating impedance is identical to the impedance of the line (matched load condition). In this case no heat is reflected at the termination and it provides a good approximation of a semi-infinite sample.

TLM MODEL OF A THIN FILM FUSE

Dimensions and boundaries

The fuse structure that was considered is shown in Figure 2. The symmetry permits one to simplify the treatment by considering one quarter of the entire problem. Figure 2 also shows the physical dimensions and the boundary analogues. [0 C] implies that the boundary is equivalent to an electrical open circuit, which is a good approximation since radiative losses are very small compared with thermal conduction. The matched load boundary (designated [M L]) has been used to simulate a structure whose horizontal dimension is very large compared to the region of maximum thermal dissipation. The matched load at the under surface of the substrate implies that it is likewise much larger than the geometry of the hottest region. For the timescales involved in the pre-arcing process this simplification is found to be valid.

The conductor

Silver was used as the electrical conductor in all simulations. In order to provide a comparison with experimental data[1] a conductor thickness of 2.2μ was used for simulations on silica. 1μ was the value used with alumina. The values of electrical resistance and its variation with temperature were derived from the American Institute of Physics Handbook[6]. Within the routine the resistivity for each discretised volume of conductor was adjusted at the end of every timestep. The adjusted value of resistance was determined by the temperature of the substrate node immediately below it.

Since the values of conductor thickness were very much less than the minimum dimension of any substrate node, the thermal contributions were initially ignored and the conductor treated only as a heat source.

Substrate

Values of specific heat and thermal conductivity were abstracted from Touloukian[7,8]. The thermal resistance, capacitance and hence line impedance were calculated for each node at the end of a time step.

RESULTS

Comparison with thermal imaging results

The three dimensional TLM routine was tested for a thin film silver element (2.2μ thick) carrying 1A DC on silica. When the calculated results were compared with experiment it was found that agreement was good only at locations remote from the region of maximum dissipation. One source of discrepancy was obviously the silver conductor itself. In the initial formulation it was ignored on the basis thatit was very thin compared with the thickness of the nearest silica node. If all node sizes were reduced to accommodate the conductor thickness the computational efficiency would have been reduced drastically. Nevertheless it can be seen that even for very thin layers, the thermal parameters of silver can make a significant contribution. If one considers the relative dimensions of a silver element and its adjacent substrate node, one can see that the silver makes a small contribution to the thermal capacitance. In the vertical direction the silica and silver thermal resistances add in series. As the thermal resistance of silver in this direction is negligible compared to the silica thermal resistance its contribution can be ignored. In the horizontal directions the two resistances sum in parallel and total resistance will therefore be dominated by that of the silver.

This suggests that the thermal effects of the conductor can be included without any loss of computational efficiency if one uses a composite surface node like that shown as an inset in Figure 3. When this was taken into account there was a considerable improvement in the extent of agreement between theory and experiment and the results for a latitudinal (x-direction) temperature profile are shown in Figure 3. Residual differences can be attributed to resolution errors. The 10 x lens used in the original measurement had a minimum resolution of 150μ. Experiments with a 40 x lens (resolution 38μ) confirms that there is a small underestimate of temperature when a 10 x lens is used on this type of structure.

The effects of thermal feedback

The influence of the insulating substrate was investigated for the pre-arcing period. For simulation purposes this was assumed to be the time necessary for the conductor to reach its melting point. TLM was used to model the case of a thin film silver fuse (of the lateral dimensions shown in Figure 2). Currents were chosen so that the 2.2μ thick conductor on silica would reach melting at about the same time as a 1μ thick element on alumina. The effect of thermal feedback for both substrates can be seen in Figure 4. The rate of temperature rise increases in the case of the element on alumina. For silica the rate of temperature decreases with time. The influence of the positive thermal feedback effect in alumina can be seen over a range of currents in Figure 5. The results suggest that a thin film fuse on alumina should be more sensitive to overloads. At 7.5A the element is in a steady state condition. There is a transition somewhere above 8A. Melting is reached within 105ms at 8.5A and within 30ms at 9A. These effects become even more significant at higher current levels. Figure 6 shows the variation of maximum temperature with time when 29A is passed through a 1μ thick silver conductor on alumina during 10ns. It is quite clear that this does not display an I^2t dependence. Tests of the model have confirmed that the behaviour is largely due to the interactions between the temperature dependence of substrate thermal parameters and conductor resistivity. A rise in temperature leads to a rise in electrical resistance and under conditions of constant current increases the dissipation rate until the melting point of silver is reached.

The effects of negative thermal feedback on a silica substrate are remarkably different. Figure 7 shows the time variation of maximum temperature when 24A is passed through a 2μ thick silver conductor. There is an initial fast rise in temperature which then settled down to an I^2t relationship. The inset provides some details about the initial thermal transient for a number of different currents.

CONCLUSION

Transmission line modelling is a fast, efficient and unconditionally stable technique for solving non-linear physical problems. Once it is mastered the user has at all times a reassuring sense of the physical nature of the problem which is being modelled; something that is not often possible with the more conventional finite difference and finite element methods.

TLM has been used to simulate the thermal behaviour of thin film fuses on silica and alumina substrates. The negative thermal feedback effect and the resulting I^2t behaviour suggests that silica is indeed a most inappropriate substrate material. Thin film fuses on alumina should represent a considerable saving in terms of the conductor required for a particular current rating. The temperature-time dependence at high current levels indicates that fuse structures based on alumina should be capable of providing protection for fast power semiconductors.

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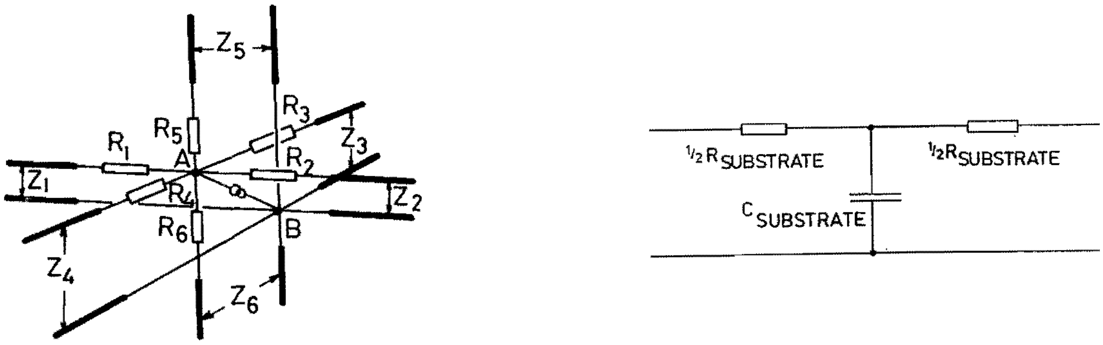

Figure 1. A three-dimensional transmission line node and a one-dimensional lumped equivalent circuit

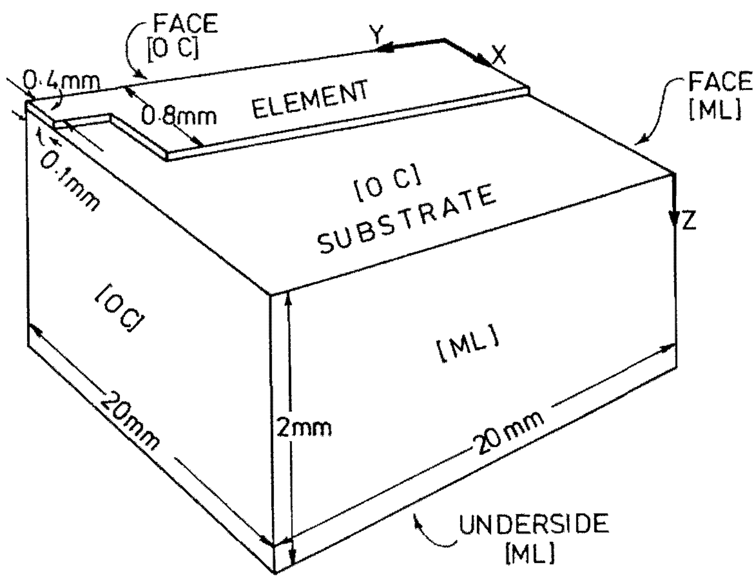

Figure 2. Fuse element and substrate used in TLM model

(b)

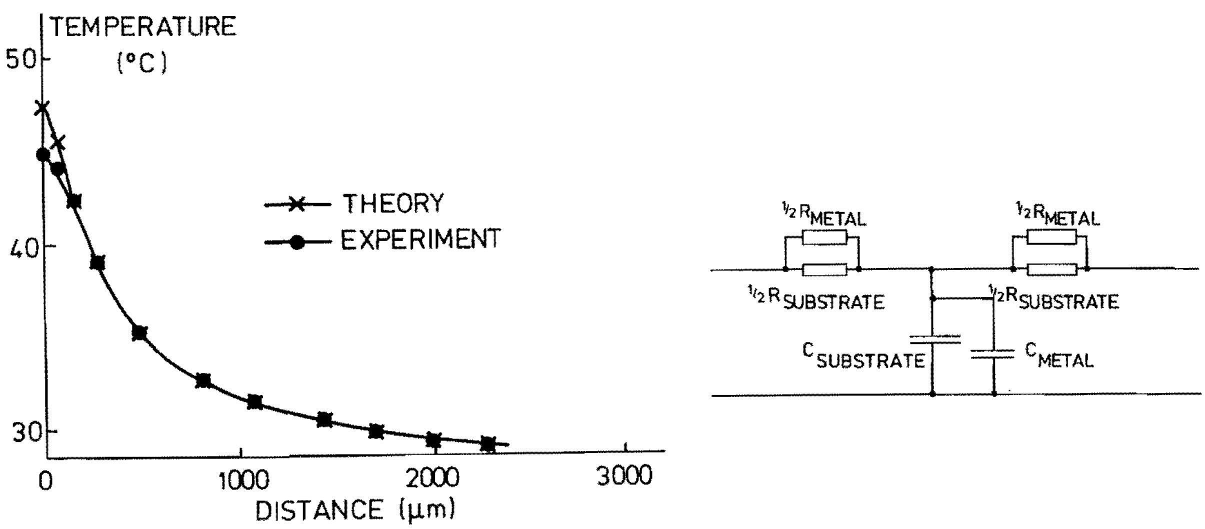

Figure 3. Comparison between theory and experiment: X-direction temperature profiles for a 2.2μ silver conductor on silica with a current of 1A. The composite surface node is shown as an inset.

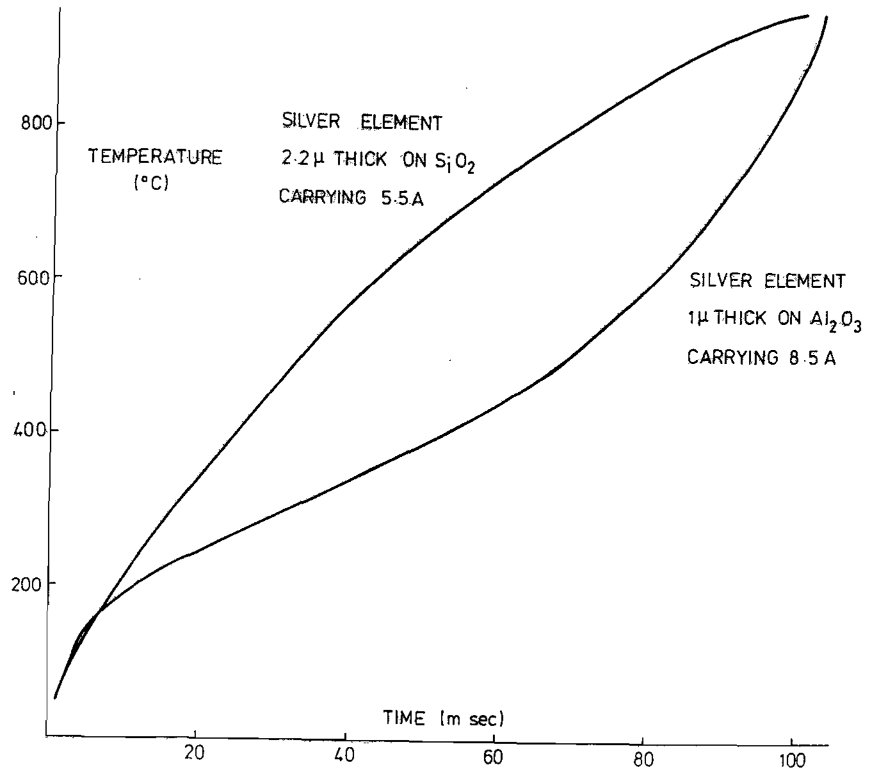

Figure 4. Plot of maximum temperature versus time for silver elements on silica and alumina substrates

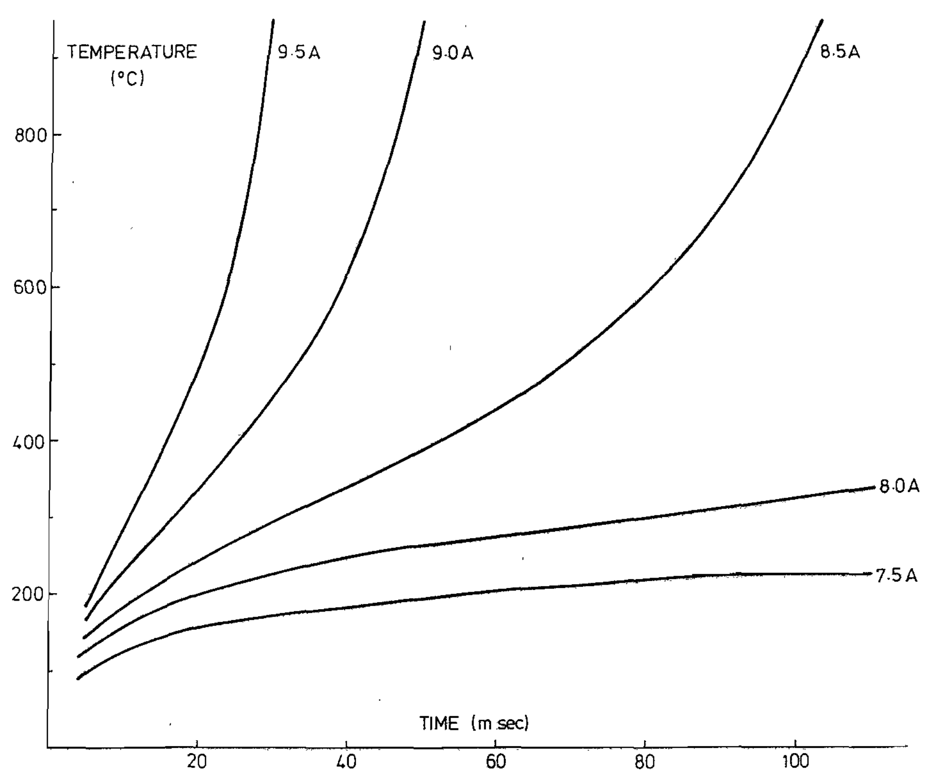

Figure 5. The influence of conductor current for silver element on alumina, plotted as maximum temperature versus time.

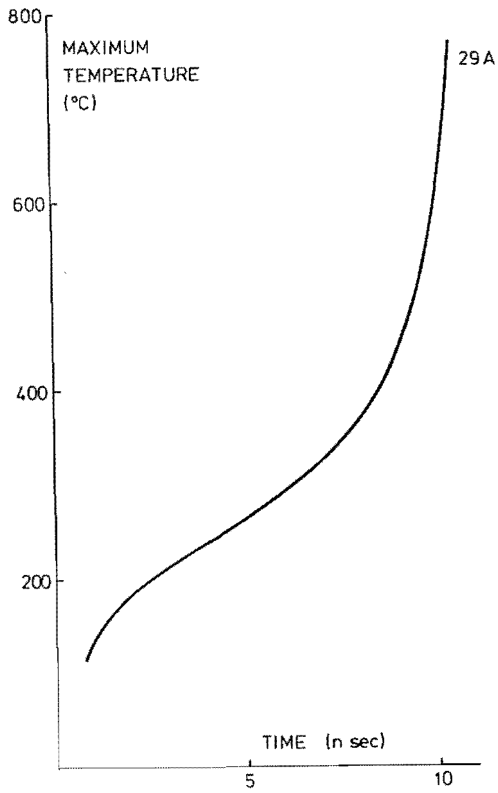

Figure 6. The variation of maximum temperature as a function of time for a 1μ silver element on alumina with a current of 29A.

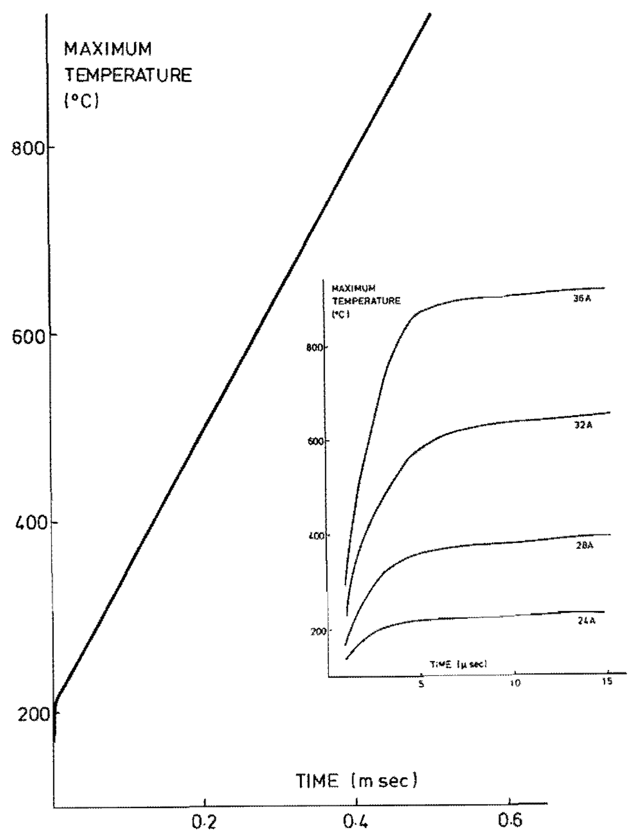

Figure 7. The variation of maximum temperature as a function of time for a 2.2μ silver element on silica with a current of 24A. The effect of current on the initial transient is shown as an inset.