FINITE-ELEMENT ANALYSIS OF THERMALLY-INDUCED FILM DE-BONDING IN SINGLE AND TWO-LAYER THICK-FILM SUBSTRATE FUSES

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Abstract: The paper presents a linear elastic finite element (FE) design tool which has been developed for evaluating the electro-thermally-induced stresses that occur in current-carrying thick-film substrate fuses and to quantify their effect on de-bonding of single conductive film from the substrate. The methodology necessitates semi-concurrent solution of the electric current distribution, temperature distribution, stress-strain distribution and displacement distribution fields throughout the substrate fuse [5, 6, 7]. Analyses of film de-bonding are given and some practical fuse design options are also examined using the tool. How the tool can be exploited to analyse the film-substrate interfacial stresses is also discussed as is a two-layer substrate fuse design for reducing the magnitude of the critical stress components.

I. INTRODUCTION

Thick-film substrate fuses are becoming more commonly used for fuse protection of power semiconductor devices [3, 4]. This type of fuse typically comprises a multi-notch metal film electro-deposited on to a non-conductive substrate. Compared to conventional fuses, film fuse designs are capable of achieving faster operation and better control of the let-through energy and the arcing voltage. However, intermittent currents found frequently in power electronic circuits, produce cyclic temperature differentials that, due to the unmatched mechanical properties of the metal film and the substrate, create high thermal stresses within the conductive film and at the film-substrate interface. De-bonding of the film from the substrate therefore occurs where the interfacial shear stresses exceed the adhesive strength of the film-substrate bond.

The FE models were constructed using PATRAN [1] and the FE solver used was ABAQUS [2]. All analyses were performed on a SunUltra 10 workstation.

II. INVESTIGATED SUBSTRATE FUSE

The electro-mechanical behaviour of a single-notch and a three-notch single layer substrate fuse was modelled. The fuse embodies an alumina substrate with a thin silver film laid on to it. Conventional quartz sand filler completely surrounded the fuse element and substrate. The geometry and dimensions of the fuse element and substrate are shown in Figure 1.

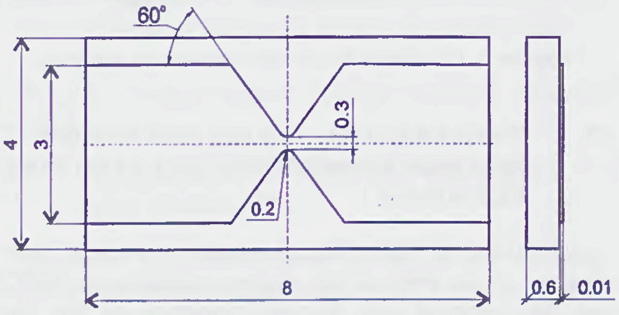

Figure 1. Geometry of the substrate fuse.

3D FE modelling was used and axi-symmetry was exploited, i.e. only one quarter of the fuse was modelled.

II.1 FE model for the thermal-electrical analysis.

The FE model for the thermal-electrical analysis comprised 31,157 finite elements. The model is shown in Figure 2 in which the film and substrate mesh are just distinguishable through the filler mesh.

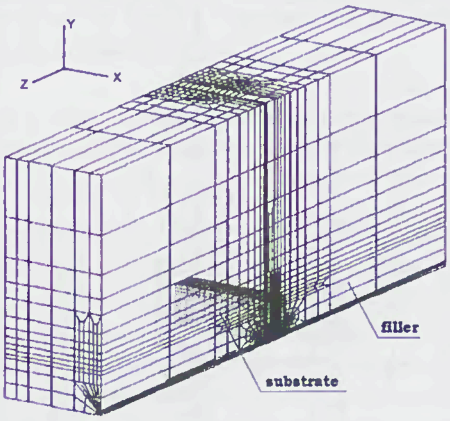

Figure 2. Finite element model for the thermal-electrical analysis.

II.2 FE model for the thermal stress analysis.

The FE model for the thermal stress analysis comprised 13,365 finite elements, of which 7,290 were used for the metal film, Figure 3. The filler mesh was omitted from this model.

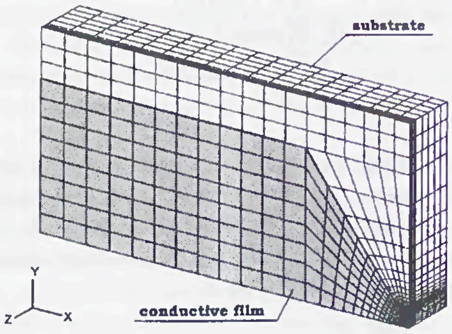

Figure 3. FE model for the thermal-stress analysis.

III. TEMPERATURE, STRESS AND STRAIN DISTRIBUTIONS IN SINGLE-LAYER FUSE ELEMENTS

All nodes on the external boundary surfaces were assumed to be fixed at the ambient temperature (20°C) and the electrical and thermal properties of the fuse materials were allowed to vary with temperature [8, 9]. Both electrical and thermal fields were solved concurrently using the **Coupled thermal-electrical* procedure of the FE solver [2]. The current was selected to produce a maximum element temperature of 200°C under steady-state conditions for all substrate fuse designs.

The critical temperature occurs at the film-substrate interface along the 'Z' symmetry axis of the model. The temperature profile of the element and filler-substrate composite along this axis is shown in Figure 4.

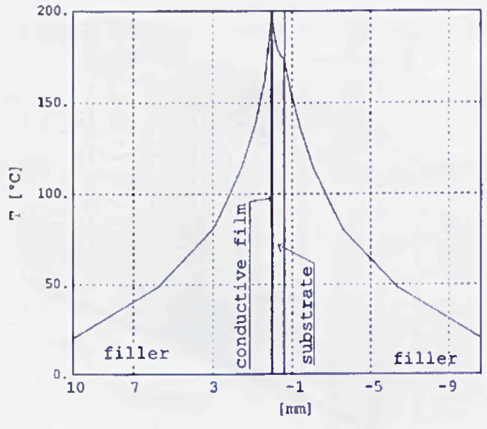

Figure 4. Temperature profile along the 'Z' symmetry axis of model.

Given that the thermal expansion coefficient of silver is approximately three times that of alumina, large shear stresses develop at the film-substrate interface.

The distribution of the shear stress σ_{zy} at the film substrate interface is illustrated and given in tabular form in Figure 5. The conductive film and filler are omitted from the illustration for clarity.

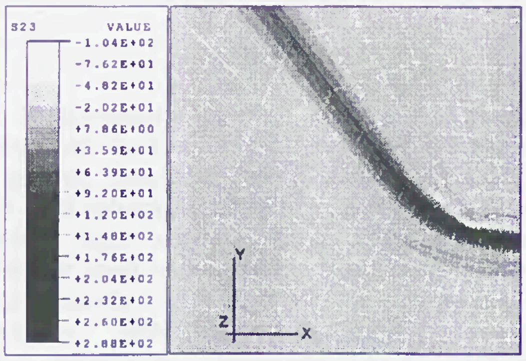

Figure 5. Shear stress σ_{zy} distribution at the film/substrate interface.

From Figure 5 it can be seen that the shear stresses are largest along the interfacial film-substrate notch edge. Hence, given that the criterion for film de-bonding is where the magnitude of the maximum shear stress exceeds the film adhesion strength, de-bonding, if it were to occur, would theoretically be initiated at the point of the maximum shear stress along this leading edge. In fact the model shows that the maximum shear stress occurs at the point along the film-substrate leading edge coincident with the minimum cross-section of the notch.

Compressive stresses are also produced within the film-substrate geometry due to the temperature increase. The compressive stresses in the conductive film produce deformation (buckling) of the film-substrate and the longer the fuse element the more pronounced it becomes. The deformation of a three-notch substrate fuse, magnified 150 times for clarity, is shown in Figure 6.

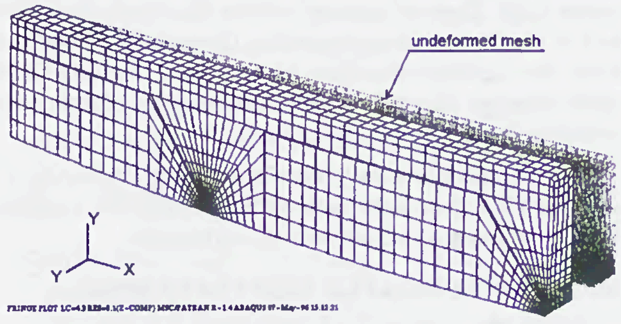

Figure 6. Film-substrate deformation in a three-notch substrate fuse (deformation magnified 150 times).

III.1 Effect of varying the film thickness on the magnitude of the stresses and deformation

The tool is a useful design aid for evaluating the effects of changing the properties, dimensions and shapes of elements on the critical stresses and, hence, on the precipitation of film de-bonding. As an example, the FE tool was used to examine the fuse design shown in Figure 1 where only the film thickness was varied. The variation of the critical orthogonal shear stress components and the corresponding displacement are shown, graphically, for three film thicknesses, in Figure 7.

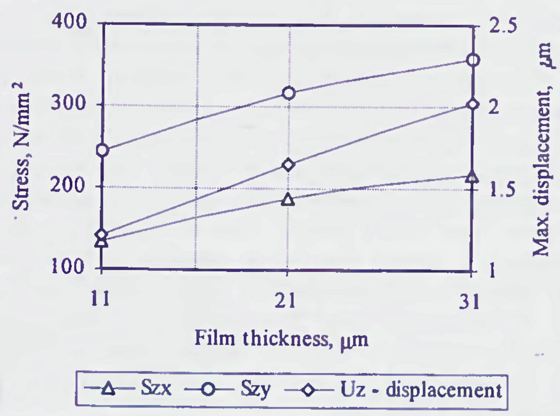

Figure 7. The effect of varying the film thickness on the magnitude of the critical stresses & displacement.

From Figure 7 it is observed that increasing the film thickness produces greater trapped stress in the film and increased deformation since the trapped stress produces greater interfacial shear stresses. Thin conductive films are, therefore, superior to thick films in this respect, i.e. thinner films produce smaller deformation and also all significant stress components are smaller in thinner film fuse elements.

III.2 Effect of varying the substrate thickness on the magnitude of the stresses and deformation

The same substrate fuse design was examined for three cases where only the substrate thickness was allowed to vary. The magnitudes of the interfacial shear stresses and the deformation for the three samples are given in Figure 8.

It is clear from Figure 8 that the substrate thickness has a significant effect on the magnitude of the deformation since as the substrate thickness is decreased the magnitude of the deformation increases markedly. This is, of course, because thinner substrates are more flexible than thick substrates. The substrate thickness, however, has no significant effect on the magnitude of the interfacial shear stresses, which increased only slightly as the substrate thickness was increased, due, mainly, to a smaller portion

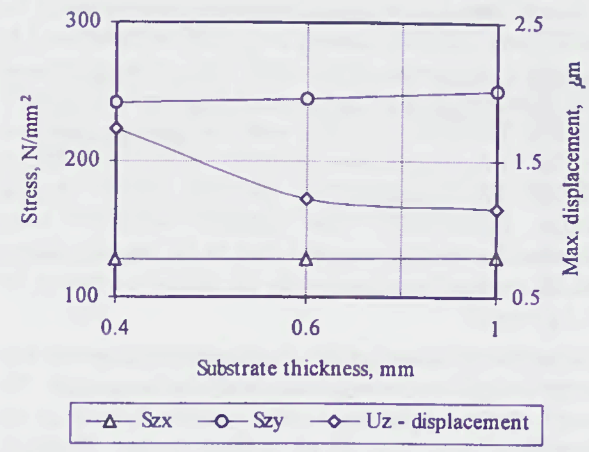

Figure 8. The effect of varying the substrate thickness on the magnitude of the critical stresses & displacement.

of the stress being released through observed substrate buckling.

IV. STRESS MAGNITUDES IN TWO-LAYER FUSE ELEMENTS

Two-layer FE film-substrate designs using different metals for the substrate bonded film (SBF) were evaluated using the tool in an attempt to reduce the interfacial stresses. The results obtained were compared with the corresponding results for a single-layer silver film of the same thickness (10.5μm). The thickness of the SBF was 0.5μm. The thickness of the main conductive silver layer, termed the metal bonded film (MBF), was 10μm and that of the substrate was 6mm, as in the previous example. The stresses can be calculated in several ways [7] depending on whether the absolute value of the stress is critical (MISES) or whether the maximum shear stress (TRESCA) is critical. The resultant stresses were determined for eight two-layer film cases, the results for which are given in Table 1, together with the orthogonal shear stress components S_{zx} and S_{zy}.

Table 1 – Stress magnitudes in two-layer samples compared with the single-layer silver film sample.

SBF	MISES N/mm^2	TRESCA N/mm^2	S_{zx} N/mm^2	S_{zy} N/mm^2
Au	434	485	125	230
Al	519	560	128	236
Mg	432	484	124	225
Ti	413	461	125	230
Cu	550	584	131	243
Mo	436	494	129	239
W	518	597	131	244
Ag	478	524	127	234

From Table 1 it is observed that the magnitudes of the MISES and TRESCA stresses are significantly affected by the elastic properties of the SBF. The greatest increase was observed for the Cu-Ag metal combination (MISES: +15.1%, TRESCA: +11.4%) with the greatest reduction for the Ti-Ag combination (MISES: -13.6%, TRESCA: -12.0%). The magnitudes of the shear stresses did not change significantly, the greatest reduction being observed for the S_{zy} stress (-3.8%) in the Mg-Ag sample and the greatest increase for the S_{zy} stress (+4.3%) in the W-Ag sample.

The effect of varying the elastic properties of the SBF on the overall stress magnitude was also examined. The overall stress magnitude, in this case, is defined as the normalised scalar sum of the critical stresses TRESCA, MISES, S_{zx}, and S_{zy}. In the examples considered, no relationship was found between either the magnitude of the overall stress and the thermal expansion coefficient or between the magnitude of the overall stress and Young's modulus. However, the overall stress is a function of the product of the thermal expansion coefficient and Young's modulus, which shows a reasonable linear relationship between the corresponding normalised stress and SBF elastic properties, Figure 9.

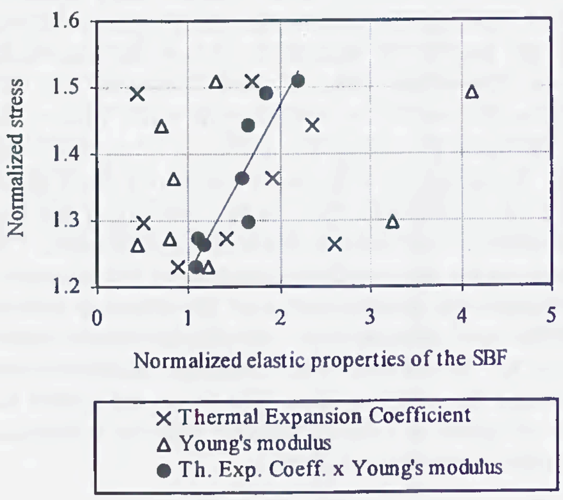

Figure 9. The effect of varying the elastic properties of the SBF on the overall magnitude of the stress.

The linear behaviour of the normalised product of Young's modulus and thermal expansion coefficient for varying elastic properties can be explained as follows:

- The larger the thermal expansion coefficient the larger is the elastic strain (defined as the difference between the total strain and thermal strain) and, consequently, the larger is the stress;
- Coincidentally, the larger the Young's modulus the larger is the magnitude of the stress for a given magnitude of strain. However, it should be noted that the strain is primarily affected by the elastic properties of the substrate and the MBF.

V. EXPERIMENTAL VERIFICATION OF CONDUCTIVE FILM DE-BONDING FROM THE SUBSTRATE

The stresses presented in previous sections were considered to be too small to produce film de-bonding from the substrate under steady-state current-carrying conditions. Increasing the current incrementally was considered impracticable in this case as it would result in the film material melting and fuse operation before de-bonding would occur. However, it was envisaged that under pulsed-current loading conditions the cyclic stresses could produce de-bonding due to fatigue. This hypothesis was investigated experimentally using a manufactured substrate fuse (MSF) design, rated at 20A/300V, which comprised a copper film on an alumina substrate. The MSF samples were subjected to a square pulsed current of 40A of mark:space ratio 50% for an ON time of 18s. Following operation, the MSF samples were dismantled and, as envisaged, de-bonding was observed in the constrictions, Figure 10.

Figure 10. Film de-bonding from the substrate.

VI. CONCLUSIONS

The paper demonstrates how a FE tool can be developed and used to design thick-film substrate fuses and to prevent the on-set of the conductive film de-bonding from the substrate. Examples of varying the dimensions of films and substrates and the film material properties have been given which, further, demonstrate the scope and generality of the design tool. In this latter respect the tool was shown to be useful for evaluating single and two-layer substrate fuses and, in the latter case, to be capable of evaluating different combinations of metal films using normalised characterisation.

Film-substrate de-bonding was taken as an example of the generality of the tool's application, since film de-bonding impairs the film-substrate thermal path and, hence, affects its electro-thermal characteristics. If not allowed for, the impairment, of course, will precipitate fuse operation and reduce the withstand capacity of this class of fuse.

The presented design evaluations indicate that large interfacial shear stresses develop in thin-film substrate fuses at the film-substrate interface due to mismatches in the elastic properties of the substrate and conductive film materials. It has been shown that the magnitude of these stresses and corresponding deformation can be computed using the FE tool for any current loading, in order to determine, for example, the criticality of the film de-bonding stresses.

The reported design evaluations were not intended to be exhaustive, however, some general principles were indicated by the presented results. For example, it is clear that (i) the stresses and deformation increase as the film thickness is increased, (ii) varying the substrate thickness has only a limited effect on the magnitude of the stresses and (iii), as a consequence of (ii), thinner, more flexible, substrates are prone to increased deformation. It was also predicted using the tool, that for the particular substrate fuse geometry examined, the deformation and stresses would not cause film de-bonding.

Finally, it was envisaged, and established by experiment and by use of the FE tool, that de-bonding of the conductive film from the substrate would occur for excessive pulsed-current loading.

VII. REFERENCES

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VII. ACKNOWLEDGEMENTS

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