AGEING OF FILM FUSES ON SUBSTRATES

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Abstract

The fabrication and long term behaviour of a simple film element fuse are described. The fuse comprised an alumina substrate with a combination of single layer screen printing and vapour deposited silver film to form the element. The fusing region was made solely from a single layer of vapour deposited silver. The long term behaviour of the fuse was tested under alternating current conditions. Although migrational affects are not normally associated with these conditions, such an effect did appear to occur. It was speculated that this migration was thermally induced by heat generation within the element. The paper further describes the effects of elevated temperature on various thicknesses of silver films, in relation to resistance changes and surface morphology.

1. Introduction

The continual development of fast-acting semi-conductor devices has made the protection of these products by fuses increasingly difficult. Consequently manufacturers have striven to produce fuses with very fast operating times and hence low let-through I^2t. Dr. Turner in her keynote speech to the Third International Conference on Electrical Fuses and Their Applications [1], pointed out that substrate fuses are capable of very high speed operation. To produce such fuses manufacturers are turning to technologies developed by the semi-conductor industry, which has experience of manufacturing good quality conductive metallic films in intimate contact with supporting, electrically insulating, ceramic substrates. The aims of this paper are to provide some insight into the viability of substrate fuses with respect to their long term stability.

De Cogan et al [2], showed that when a thin film fuse element is in intimate contact with a thermally conductive substrate, heat is dissipated from the hot element through the substrate allowing the elements to carry, in steady state, higher current densities than are possible with conventional fuse element designs surrounded by granular quartz. However, under fault conditions, the small cross-sectional area of the film element, ensures rapid operation. Both the thermal and mechanical properties of the substrate are of paramount importance in affecting the overall fuse characteristics [3], [4]. De Cogan et al have shown that materials whose graphs of thermal time constant vs temperature, have positive slopes (e.g. alumina), are far more suitable for rapid fuse operation than those with negative slopes (e.g. silica). Since, in the former case, the heat generated during steady state conditions is readily dissipated from the restriction. Whereas under fault conditions the rate of heat dissipation is used to heat and vaporise the element. As the steady state fuse current is very dependent on the heat dissipation, the time vs current curves of this type of fuse are difficult to compile because their performance is greatly affected by the cooling provided for each element [5].

2. Initial Test Observations

Test samples were made by evaporating silver through a patterned foil mask, onto commerical grade alumina substrates. The silver element layout is shown in figure 1. These fuses were subjected to long term a.c. tests, and preliminary results indicated that these fuses were failing prematurely. On examination of the elements with a scanning electron microscope, surface features were found which suggested that migrational effects may have caused the unexpected operation of the fuses.

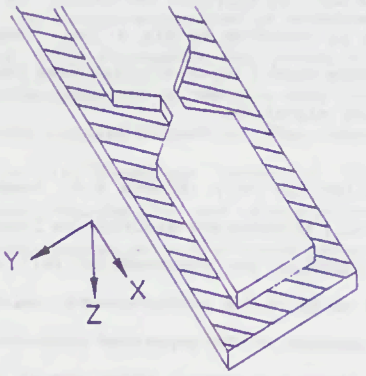


FIGURE 1.

SUBSTRATE FUSE ELEMENT
RESTRICTION IN X-Y PLANE.

To enhance any possible migrational effects a special type of substrate fuse was constructed. Instead of forming the constriction in the width of the silver film as was done in the previously described substrate fuse, the constriction was formed in the thickness plane (or "Z" direction), of the film. This is illustrated in figure 2.

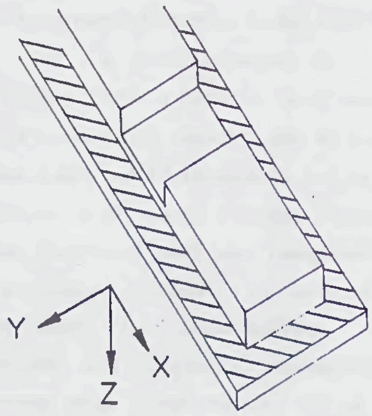


FIGURE 2.

SUBSTRATE FUSE ELEMENT
RESTRICTION IN Z PLANE.

3. **Tests on Substrate Fuses by Other Workers**

When single layer, silver element, substrate fuses were operated in d.c. circuits it was observed by Inameti [4] that there was a depletion of conductor material in the region of the restriction which was connected to the negative terminal of the supply. This reduction of conductor material was accompanied by an accumulation of material on the other side of the restriction. Inameti believed that this phenomenon was due to electromigration. To suppress the effect, he added thin super layers of chromium to his films. Whereas other authors [6] have used a layer of glass over the conductor to prevent any migration.

This problem not only affects d.c. fuses but also manifests itself in the micro-electronics industry, where integrated circuits are reported to fail due to the formation of voids in the interconnects, which have been caused by migration of the deposited conductor [7]. For this reason there has been a large amount of research into this effect.

Electromigration is found to be a major problem in thin film conductors because of the associated high current densities which can normally be in the region of 10^4 A/mm^2. The phenomenon does not arise from any material transport caused by chemical potential gradients [8], but is caused by an interaction between the atoms of a conductor and a d.c. current flowing through the conductor. Electromigration, like other transport phenomena, in thin films often occurs via grain boundary diffusion. It is generally considered that the driving force behind the transport phenomenon is a combination of two effects. Firstly, there is an electrostatic interaction between the applied electric field and the ionic core of the atoms which have been stripped of their valence electrons, and an electrostatic frictional force between these ions and the flowing charge or current of electrons passing through the material.

Some workers [9] have noted a temperature dependence of electromigration by measuring an activation energy for the process, ΔH. Their results indicated that for thin silver films at a temperature between 225°C and 280°C, ΔH was approximately 0.95eV, which they suggested was typically due to ion movement in the grain boundaries. Whereas, at lower temperatures 160°C to 225°C, the reported value of ΔH was 0.3eV which they assigned to surface dominated transport.

4. **Fuse Fabrication**

To produce a large aspect ratio at the restriction with the "Z" fuse (in figure 2.), conductive screen printed material was laid onto commercial grade alumina substrate (dimensions of 52mm x 14mm x 0.63mm) to a thickness of between 12 and 14 µm, in two or more rectangular patterns each separated by 2mm. After ultra-sonic cleaning in acetone, the samples were mounted in a vacuum chamber which was evacuated to a pressure of about 1×10^{-3} N/m^2 (1×10^{-5} mbar). Silver was then evaporated onto the exposed surfaces using an electrically heated tungsten boat to produce a fusing region which had a uniform thickness across the restriction. The thickness of the silver layer, which was controllable to an accuracy of 5nm, was between 0.25µm and 2.0µm for the current series of experiments.

The resulting film of silver is poly-crystalline in nature and each grain containing silver atoms arranged in a face centred cubic arrangement [10]. The size of the grains can to some extent be changed by altering the deposition conditions. The rate of deposition used was in the order of 2.0nm/s. The adhesion of the silver to the alumina substrate was found to be adequate and therefore, it was unnecessary to deposit an intermediate layer of chromium as employed by Inameti [4].

5. Long Term Ageing Effects

To assess the long term ageing effects of substrate fuses under a.c. conditions, it was necessary to examine an element immediately before the onset of arcing, since arcing would destroy any features of ageing in the fusing region of the silver element. To ensure that an element would be as close as possible to the poiht of operation without actually operating, two identical elements (within normal fabrication tolerences) were connected in series, so that when one fuse operated the other one was left in its aged but intact state. This approach ensured that there was no interference to a healthy restriction from the arcing and has proved to be more reliable than the examination of undamaged restrictions in multi-restriction elements which had operated.

A separate screen printed area was put on the reverse side of the substrate along the complete length. This area was then soldered to a solid copper base. To provide good electrical connections, copper connecting tags were soldered to the screen printed areas at each end of the element, see figure 3.

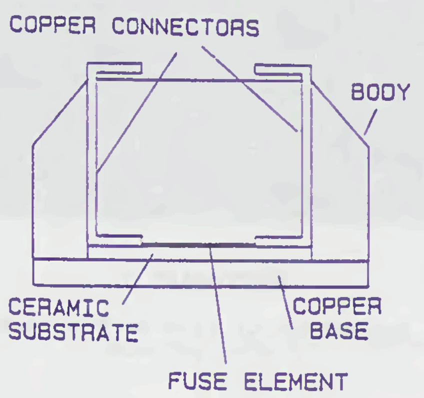


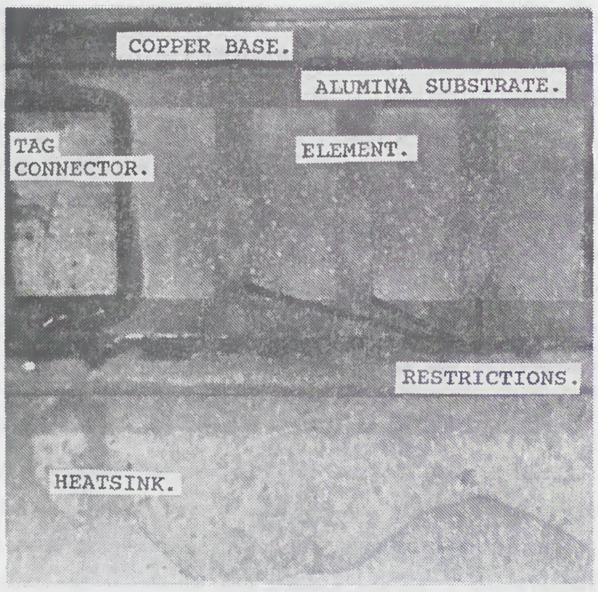
FIGURE 3.

FUSE CONFIGURATION.

Two nominally identical fuses from a batch, each with fusing area dimension, 2mm long, 12mm wide and 1.0 μm thick, were immersed in granular quartz, and then clamped to a fan cooled aluminium heatsink.

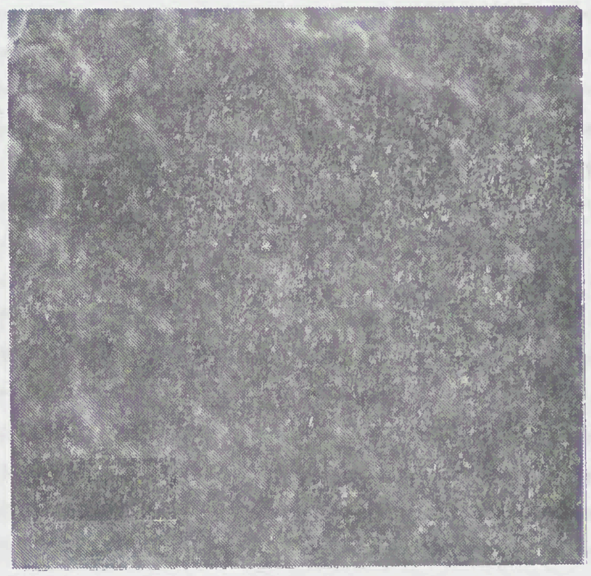
Over a period of about 1500 hours, the current through the fuses was gradually increased (~1A/day) from about 40A, until operation occured in one of the elements. An average current density just prior to operation was in the order of $8x10^3 A/mm^2$ which corresponded to a current of approximately 95A. At this current level the heatsink temperature was around 50°C.

The fuses were removed from the heatsink and examined. Initial visual studies showed that the elements had tarnished slightly and the silver had taken on a pale yellow shade in places. Due to the non-uniformity of temperature along the element the extent of tarnishing varied. A distinct oval pattern was observed in the area of the restriction. In the region where the temperature is the highest one would expect the greatest amount of oxidation. It is therefore believed that the oval pattern showed the hottest regions. These patterns can be seen in photograph A. Further examination of the elements particularly in the fusing region, was undertaken with a scanning electron microscope. The results of which appear in photographs B to F. Although the fuses were subjected to alternating current the photographs show what appears to be migration of the material in the vapour deposited restriction. It can be seen in these photographs that there is random crystal growth, with some of the crystals appearing to be shaped like long whiskers (see photograph F). These crystals are occasionally seen in electromigrated films [11]. This is interesting since the fuses were operated in a.c. conditions and one would not expect electromigration effects. As electromigration is associated with d.c. conditions, this phenomenon can probably be discounted here, and the migration of the film seen in the photograph was possibly induced thermally. The temperature at the restriction in substrate fuses is higher than in conventional designs [3], and this elevated temperature may aggravate migration in the fusing region, as described above.



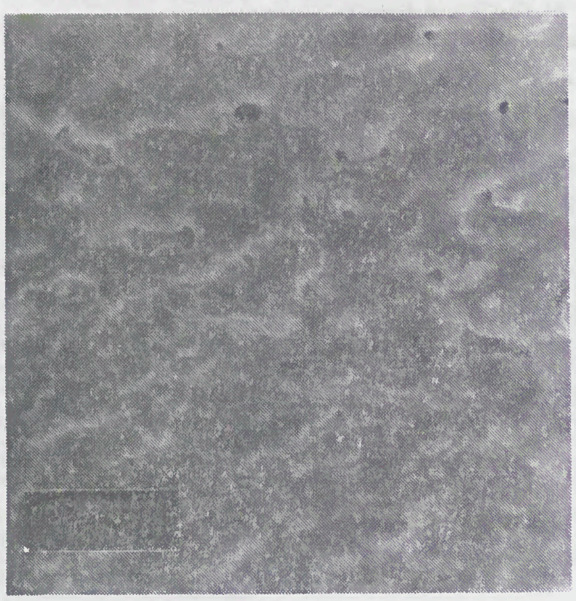
PHOTOGRAPH A.

This shows degradation of the film as oval patterns on the restrictions.



PHOTOGRAPH B.

Appearance of 1.0μm of silver film on alumina substrate, immediately after deposition.

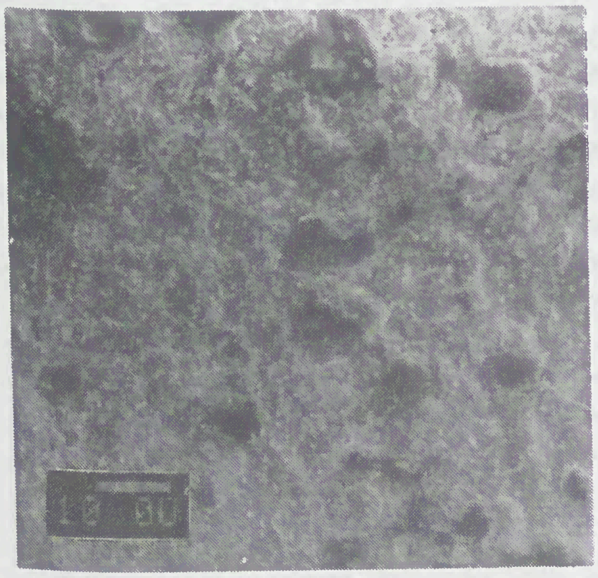


PHOTOGRAPH C

Edge of restriction showing screen printed area (top) and vapour deposited film (below)

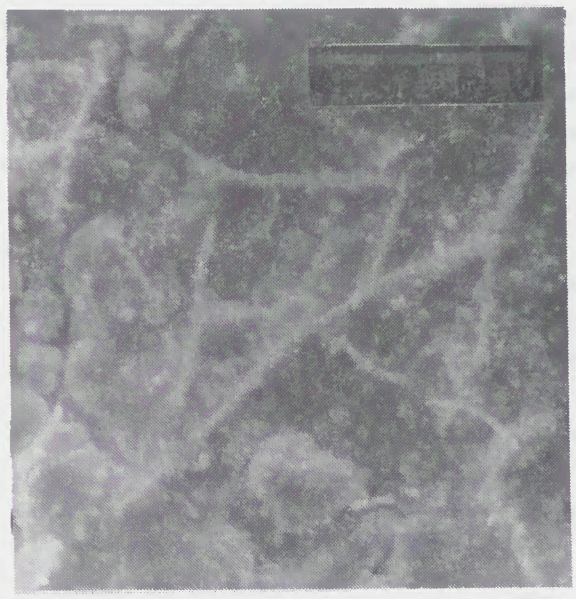
PHOTOGRAPH D.

Appearance of film at the edge of oval pattern.



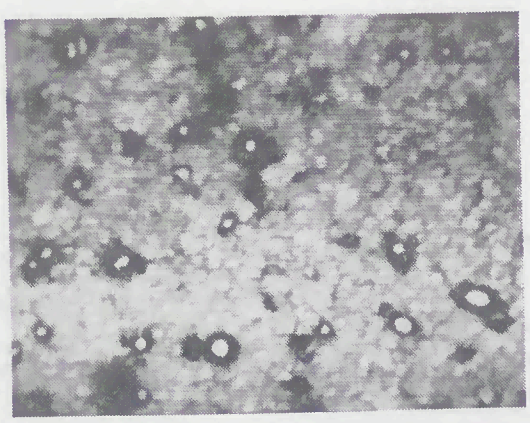
PHOTOGRAPH E.

Silver film at the centre of oval pattern showing migration features.



PHOTOGRAPH F.

Detail picture of migration showing whisker growth.



PHOTOGRAPH G.

Typical migration of heated films

6. Thickness Dependence of Migration

To find the changes in fuse resistance a four terminal system (sometimes called a four point probe) was used. A small direct current (which had a negligible heating effect) was supplied to the element via two terminals and the voltage across the restriction was measured via the other connections. Long term changes in the resistance were monitored using a digital multimeter which had been interfaced to a microprocessor.

Each film was heated by passing current through the electrically conductive screen printed strip on the reverse side of the substrate.

Figure 4 shows the results for tests done on elements with various thickness in the fusing region. All measurements were performed in a draught free environment and the substrate temperature was about 350°C. It took on average 3 minutes for the temperature of the heater to reach steady state and this accounts for the depression in the curves in the graph at points labelled A. This fall in resistance may be attributed to annealing of the film with the relief of stress which had built up during condensation of the film from silver vapour. This may have been avoided if the silver had been evaporated onto heated substrates. At point B on the graph there is a second drop in resistance followed by a much steeper rise (labelled C) at which point it is thought that migrational features begin to appear. Examination of the films after they have passed point C (figure 4) show spherical growth on the silver surface. This can be seen clearly in photograph G as dark circles, and is thought to show crystallisation of the film.

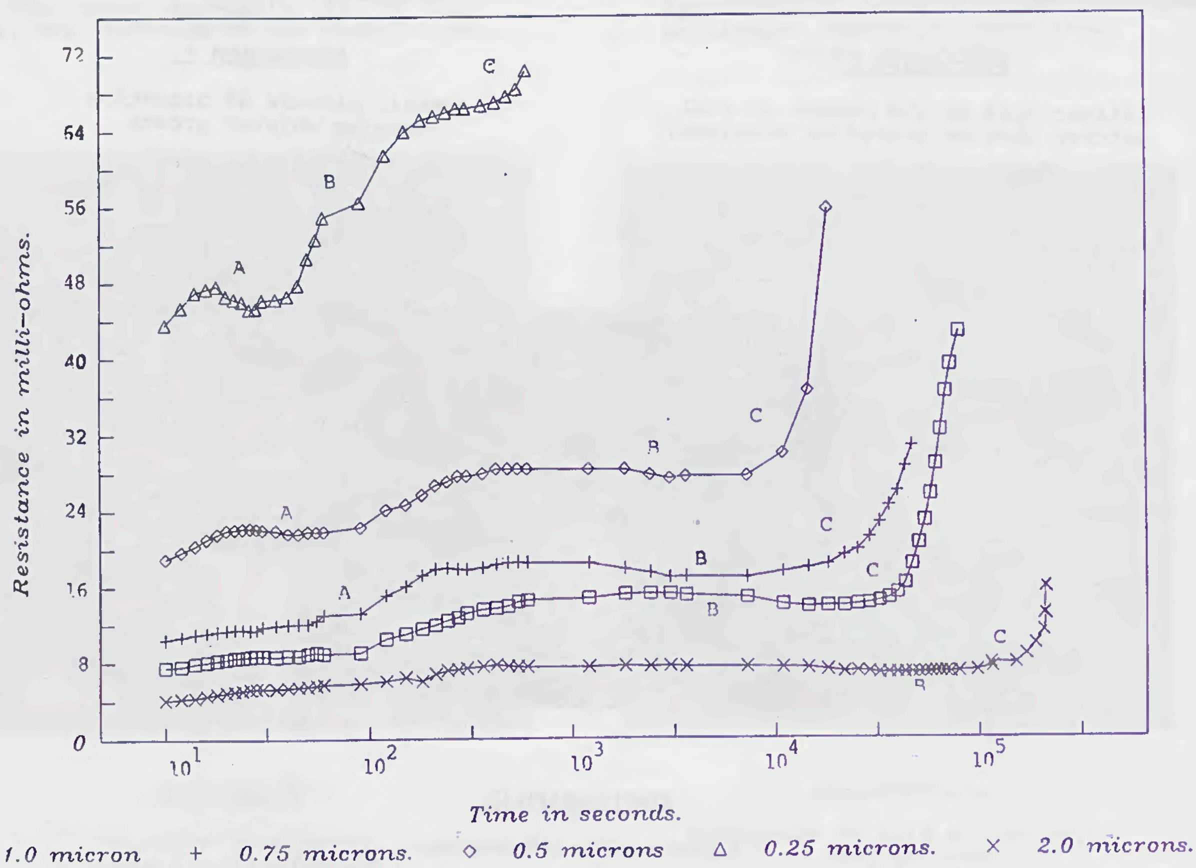


FIGURE 4.

RESISTANCE CHANGES OF FILMS UPON HEATING

7. Discussion

The effects described above show that if a substrate fuse, with a single layer element design is used in a.c. applications, then migration of the element material, particularly in the fusing region, could pose a long term problem. The onset of migration at an elevated temperature was shown to be related to the thickness of the film with the thicker films remaining stable for longer periods. It may be possible to inhibit the migrational effects by the use of vacuum deposited super-layers over the elements, alternatively the silver film element can be made sufficiently thick to make any migrational effects insignificant. Research in this field is therefore continuing.

8. Acknowledgements

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9. References

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