AGEING MECHANISM OF FUSES FOR SEMICONDUCTOR PROTECTION

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Summary

The paper describes a general method for lifetime predictions for semiconductor fuses, where fuses are subjected to short current pulses. Thermal buckling of the element due to electric currents is discussed and considered as the main reason for ageing. Agreement has been found between theoretical predictions and observations.

1. Introduction

For the protection of electrical circuits and installations, electric fuses are widely used. A fuse normally consists of fuse elements, a ceramic body and metal contacts. The fuse element is usually positioned in sand fillers. In service, fuse elements undergo deformations due to mechanical, physical and chemical effects. This leads to changes in their electrical behaviour. Consequently, the investigation on the fuse reliability becomes one of the attractive subjects because of practical interest and theoretical importance.

When fuse elements experience electric currents, thermal effect and electromagnetic reaction may be involved. Because of joule heating, the temperature of the fuse element rises. At elevated temperatures, element materials are easily deformed. Electromagnetic forces are directly contributed from the electric current carried by the fuse element. Deformation is thus dependent on the current itself. Both can lead to damages of fuse elements and hence fuse characteristics may be deteriorated.

For cyclic loading situations, Manson-coffin law presents an approximation between cyclic plastic strain and the number of cycles to failure. The law was introduced as a basic relationship to correlate the fuse lifetime with current [*Arai, 1984*] and a combined variable of temperature [*Wilkins, 1991*]. Recent studies show that for small wires to accumulate the plastic deformation, the fracture acts in a brittle fashion [*Pao, 1992*]; only for long current periods the creep induced plastic deformation becomes dominant [*Meng, 1995*].

To achieve better effectiveness for the protection of systems, it is therefore necessary to get an insight of deformation mechanism of fuse elements and to improve the reliability of fuses. Another method is to reach a good coordination between the protected systems and fuses. In this work, attempts to improve fuse reliability will be described.

Commercial fuses for the semiconductor protection were chosen as test objects. The rated current of silver fuse elements was 160 A. The fuse element dimensions are shown in figure 1. For the determination of parameters in theoretical models, a simplified fuse element with one row of notches was used. The objective of this work is to define the basic concepts related with experimental phenomena and results. Attempts will be described to explain the deformation influence on fuse lifetimes and to correlate the number of current pulses which fuses can withstand with parameters of the current.

2. Theory

When fuses are subjected to current pulses, temperature rise brings about thermal strain due to thermal expansion. The strain produces stress, because the end caps and sand impose the constrains on the fuse elements. The thermal stress fatigue is only of cyclic nature, as long as the time period for each current pulse is short enough. As the thermal stress is above a certain value, the fuse element tends to move and leaves its previous position. This process is called as thermal buckling because of its thermal origin. The mechanical strain reduces accordingly due to thermal buckling. During thermal buckling, only a part of the thermal strain is contributed to the mechanical strain to produce the stress. Therefore, to predict the lifetime, the temperature distribution and the thermal buckling behaviour should be studied.

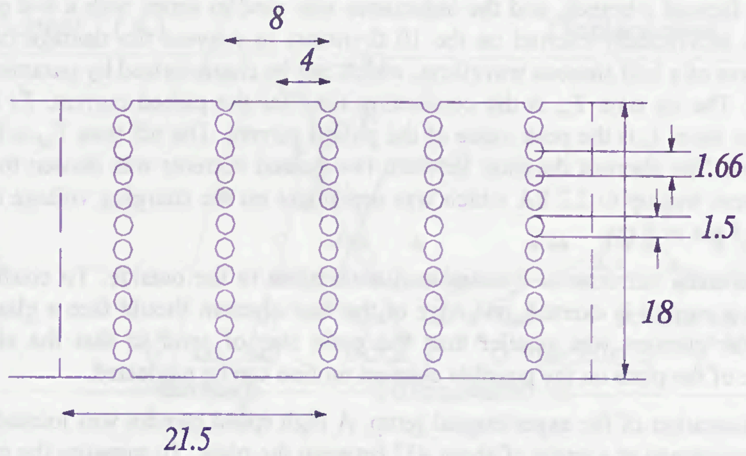

Figure 1 Geometry of fuse element (units in mm)

2.1 Temperature distribution

As a tool, EMTP (Electro-Magnetic Transient Program) was used to simulate the temperature distribution [*Meng, 1995*]. Because of symmetry, for short current pulses in order of 10 ms, a small region was simulated. A typical temperature distribution (the maximum temperature T_{max} = 574 °C) is shown in figure 2 at the time instant t = 7 ms during a current pulse with the effective current I_{eff} = 1250 A for 10 ms. For different I^2t values of current pulses, results of the maximum temperature rise can be obtained.

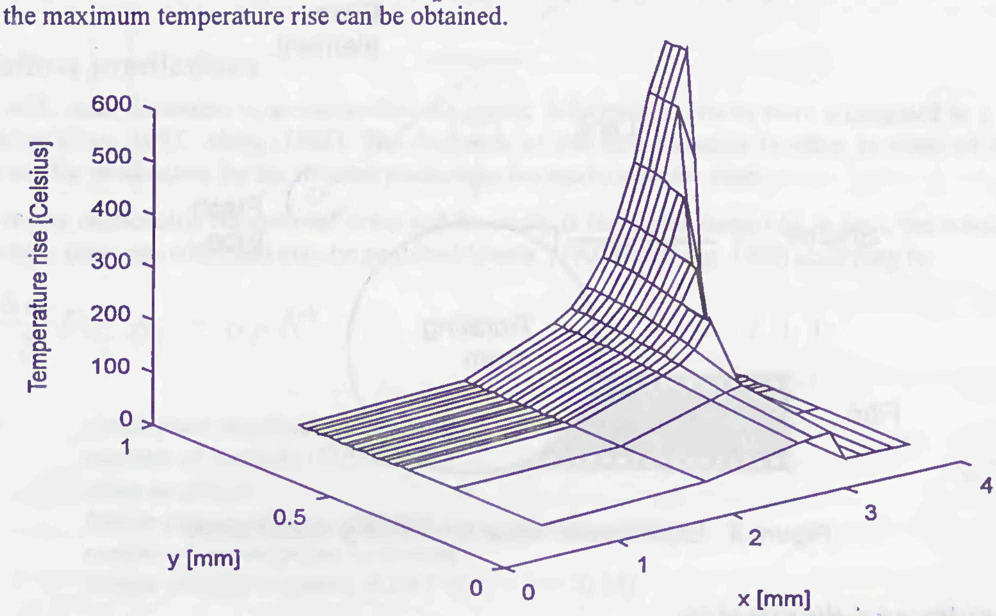

Figure 2 Temperature distribution in the notch region (t = 7 ms, I_{eff} = 1250 A)

2.2 Thermal buckling behaviour

To understand physical phenomena related buckling, quantitative observations should be provided from experiments. Because the element has five rows of notches in the commercial fuses, it is difficult and time consuming to determine the displacement for every row at different currents. For this reason, straight fuse elements were proposed, which were composed of only one row of notches in the middle.

2.2.1 Experiments

To produce a pulsed current, a simple RLC circuit with ten parallel capacitor branches was realised. Basically a capacitor and a thyristor formed a branch, and the inductance was used in series with a test object. The triggering signals of 120 mA were individually exerted on the 10 thyristors to prevent the damage of thyristors. The test current from the circuit was of a half sinuous waveform, which can be characterised by parameters as I^2t, I_p, T_{on} (on time) and T_{off} (off time). The on time T_{on} is the conducting time for the pulsed current. I^2t is the integral of the current square over the on time. I_p is the peak value of the pulsed current. The off time T_{off} is the time between two successive pulsed currents. The shortest duration between two pulsed currents was chosen to be about 2 minutes. The peak value of a current was up to 2.2 kA which was dependent on the charging voltage of capacitors. The on time can be chosen to be 5 ms or 9 ms.

Fuse elements are normally surrounded by sand and not visible to the outside. To confirm whether the fuse element moves or not as a current is exerted, one edge of the fuse element should face a glass plate. The distance between the plate and the element was smaller than the grain size of sand so that the element can be easily monitored. The influence of the plate on the possible element motion can be neglected.

Figure 3 shows an illustration of the experimental setup. A high speed camera was located in front of the glass plate. A flash light was positioned at a angle of about 45° between the plate. To measure the exact exposure time, a light detector was used to pick up the light signal. A digital oscilloscope was used to record fuse current, voltage, a triggering signal for the camera (shutter) and a signal related with the exposure period due to a flash light.

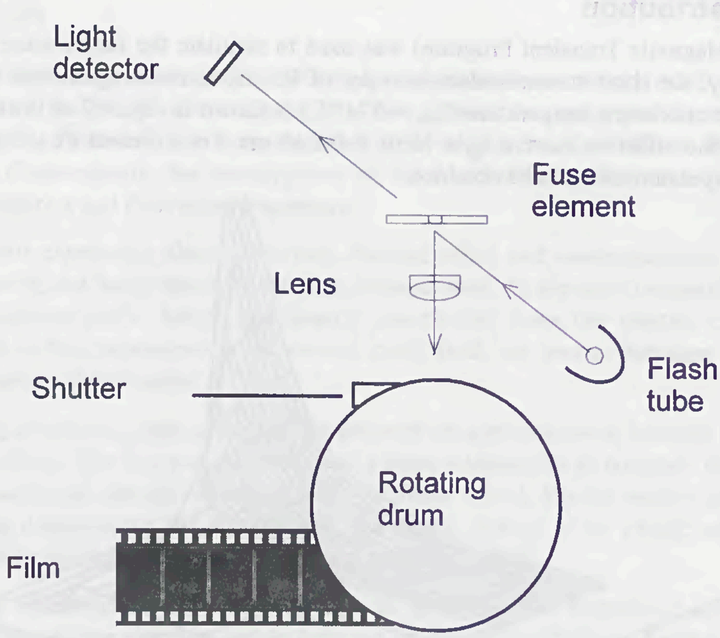

Figure 3 Experimental setup for buckling observations

2.2.2 Results and discussion

Figure 4 shows typical movements of the element together with the pulsed current against time. The element started to move in about 2 ms, after the current was exerted. Slightly after the current peak, the element arrived at the maximum displacement. As the current decreased, the element moved gradually backwards and forwards to its original position. Displacements at the element notch were measured for different I^2t values of pulsed currents. The maximum displacement was found to increase with the I^2t value of pulsed currents. From these measurements, the motion starting moment can also be determined as a function of the I^2t value of pulsed currents.

This graph shows that as I^2t values of pulsed currents exceed a certain value, motion of the element in sand takes place. The effect can be explained by the increase in thermal expansion due to temperature rises. Because of sand grains, it might also expect the element to move among grains, however, such a motion requires very high force in the axial direction. For the commonly used sand sizes (several hounded micrometers in diameter), this condition can not be fulfilled. Experiments also show that the displacement is rather smooth along the element.

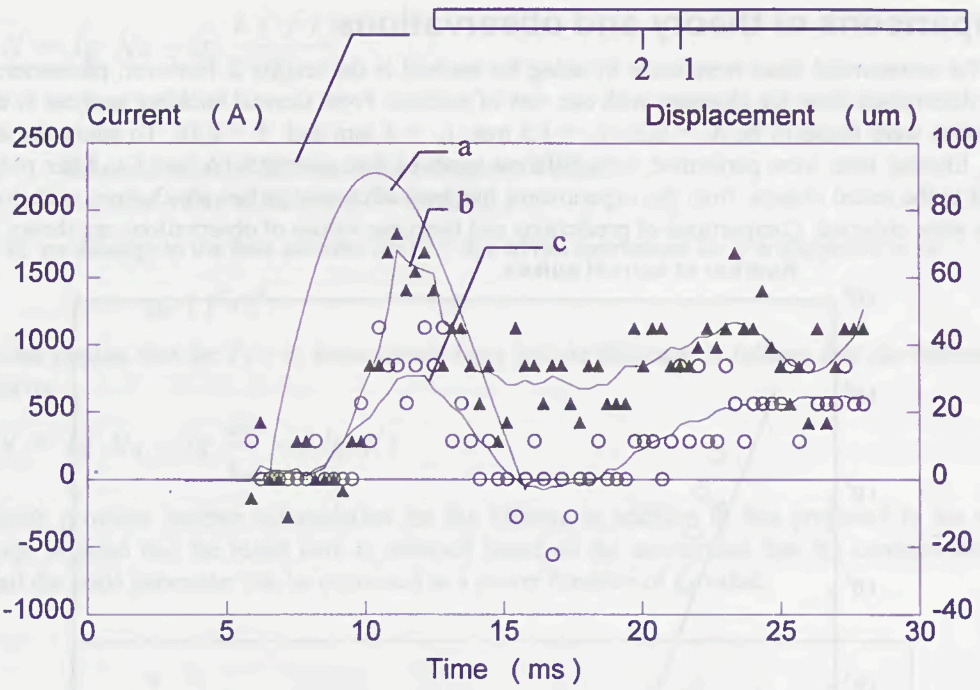

Figure 4 Measured dynamical displacement induced by pulsed current
a : current; b (Δ), c (o) : displacement at the location 1, 2;
Distance between location 1 and location 2 is about 1 mm.

2.3 Lifetime predictions

For wires with small diameters to accommodate the plastic deformation, cracks were propagated in a more or less brittle fashion [*Pao, 1992; Meng, 1995*]. The thickness of the fuse elements is often in order of 150 µm, this suggests a similar mechanism for the lifetime predictions for semiconductor fuses.

Based on the relationship between the stress and the strain in the elastic range ($\Delta\varepsilon_e = \Delta\varepsilon_T$), the number of current pulses N which fuses can withstand may be predicted [*Smith, 1962*; *Hertzberg, 1989*] according to

$$\frac{\Delta\varepsilon_e}{2} E = \sigma_a = \sigma_{f'} N^b \qquad (1)$$

where

$\Delta\varepsilon_e/2$	elastic strain amplitude ($\Delta\varepsilon_e = \Delta\varepsilon_T$)
E	modulus of elasticity ($71*10^3$ MP_a)
σ_a	stress amplitude
σ'_f	fatigue stress coefficient (130 MP_a)
N	number of current pulses to blowing
b	fatigue strength exponent -0.08 ($-0.07 < b < -0.15$)

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

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

where β is thermal expansion coefficient ($19.68*10^{-6}$)
A_0, l_1, and l_2 are constants

The mechanical strain is simply to take the form

$$\Delta\varepsilon_T = \delta\, \Delta\varepsilon_{th}$$

where δ is the deflection factor (0.7 ~ 0.95).

3. Comparisons of theory and observations

Predictions for commercial fuses were made by using the method in the section 2, however, parameters A_0 , l_1, , l_2 and δ were determined from the elements with one row of notches. From thermal buckling analysis in the section 2, these parameters were found to be $A_0 = 0.23$, $l_1 = 1.5$ mm, $l_2 = 4$ mm and $\delta = 0.88$. To study the deformation mechanism, lifetime tests were performed with different types 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. Comparisons of predictions and the mean values of observations are shown in figure 5.

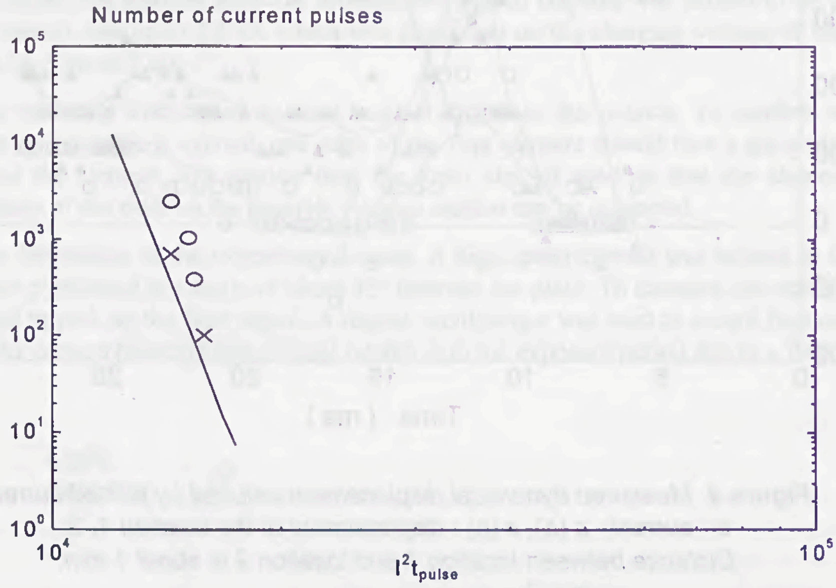

Figure 5 Comparisons of predictions and observations
"x" : type A; "o" : type C

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

4. General discussion

4.1 Lifetime distribution

Because so many parameters influence the deformation of fuses, statistical approaches are also used to resolve the problem of lifetime predictions. Figure 6 shows lifetime distributions on Weibull paper for a typical fuse element for different I^2t values. It may be seen that in general the data are well fitted with straight lines on the Weibull probability plot. It is therefore concluded that the lifetime distribution obeys Weibull distribution.

For different types of fuse elements, the slope parameter of lifetime distribution estimated according to Weibull distribution are often found to vary with the I^2t value of current pulses as shown in figure 6. However, it also has been noticed that for some type of fuses, this slope keeps the same. In attempting to present a simple relationship between lifetime and $I^2\,t$ value, the slope is taken to be constant. From this point, the ratio of mean lifetimes $E[\tau(I^2t)]$ is given by

$$\frac{E[\tau(I^2 t)]}{E[\tau(I^2 t_0)]} = \frac{\lambda_0}{\lambda(I^2 t)}$$

where

I^2t_0: the reference I^2t value

λ_0: the scale parameter of Weibull distribution at I^2t_0

further the relationship is expressed as

$$lg\,N = lg\,N_0 - lg\,\frac{\lambda\,(I^2 t)}{\lambda_0}$$

where

N_0: the mean value of lifetime at the reference I^2t value

N: the mean value of lifetime ($N = E[\tau(I^2t)]$)

Because of no damage to the fuse element for $I^2t = 0$, a trivial expression for λ is suggested to be

$$\lambda = a_0\,(I^2 t)^k$$

This expression implies that for $I^2t = 0$, fuses should have infinite lifetimes. It follows that the lifetime N can be approximated by

$$lgN = lg\,N_0 - lg\,\frac{a_0}{\lambda_0} - k\,lg\,I^2 t$$

This relation provides another extrapolation for the lifetime in addition to that proposed in the section 2. It should be kept in mind that the result here is obtained based on the assumption that the constant slope or shape parameter and the scale parameter can be expressed as a power function of I^2t value.

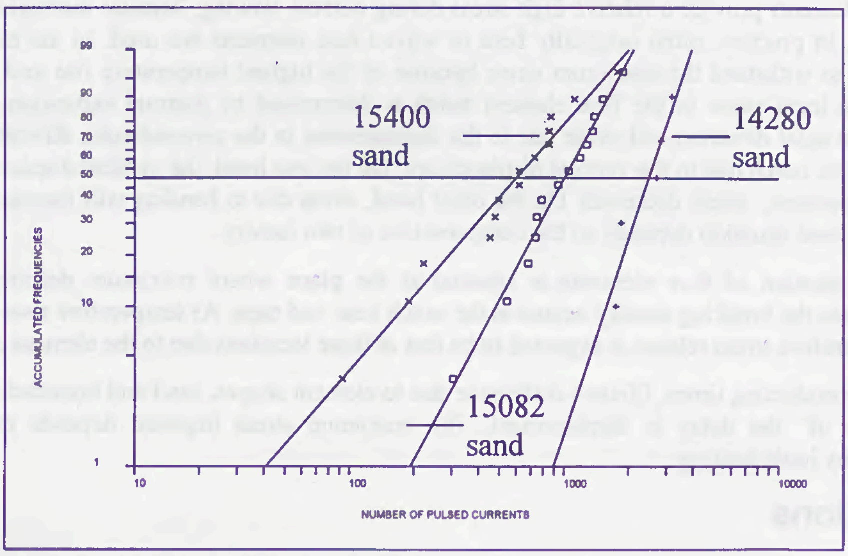

Figure 7 Lifetime distributions on the Weibull probability plot for type C elements at different I^2t values

4.2 Comparison with other authors

Using different expressions of λ may lead to the different lifetime relationships:

(1) λ is dependent on the temperature rise θ of the fuse element

$$\lambda = a_0\,\theta^k$$

(2) λ is dependent on the temperature rise θ and the average temperature θ_{av} at the hottest spot of the fuse element

$$\lambda = a_0\,\left(\theta\,\theta_{av}^x\right)^k$$

where a_0, x, k are constants

From the first assumption, the lifetime relationship similar to [*Arai, 1984*] can be achieved, while from the second assumption the lifetime relationship similar to [*Wilkins, 1991*] can be obtained.

4.3 How to avoid ageing

Ageing is a time dependent process. Effects of long time loads on the lifetime consuming is mainly to be of creep nature (including diffusion and oxidation)[*Meng, 1995*]. For short time loads, lifetimes are considered to be consumed due to cyclic fatigue related with strain variations [*Meng, 1993*].

As ageing due to temperature rises is concerned, perhaps, the maximum temperature can be proposed as one factor for design and using fuses according to the deformation mechanism map. For temperature below 200 °C, there will be no plastic deformation for silver elements. On this basis, fuses should be designed to carry currents which do not produce overheating. For fuses exerted with the rated current (160 A), a temperature rise of 200 °C is found from the EMTP simulation. Therefore, in theory this means the fuses will have infinite lifetimes.

The argument is that deformation mechanism maps are established at a rather slow heating up process, is the result relevant to fuse applications? According to observation provided in the reference [*Williams, 1982*], during the rapid heating up diffusion may occur on the grain boundaries, because of inhomoginous material construction. That means that the criteria from the deformation map is only valid for the small current carrying ability and constant loads.

Because of cyclic effects, temperature variations produce deformation even at the lower temperature, as a consequence, lifetime reduction can not be avoid. The question is how to design an element shape with the optimal lifetime.

Straight fuse elements provide a relative high stress during current flowing, because thermal expansion can not be released easily. In practice, often originally bent or waved fuse elements are used. In the most situations, the element notch has to withstand the maximum stress because of the highest temperature rise and the smallest cross sectional area. The local stress in the fuse element notch is determined by thermal expansion, strain due to the displacement in the axial direction and strain due to the displacement in the perpendicular direction. Another factor is the curvature at the notch due to the vertical displacement. On the one hand, the vertical displacement will release part of thermal expansion, stress decreases. On the other hand, stress due to bending will increase the stress on the outer surface. The final situation depends on the compensation of two factors.

The breaking location of fuse elements is situated at the place where maximum deformation is induced. Experiments indicate the breaking usually occurs at the notch near end caps. As temperature rises near end caps are not the highest, therefore stress release is expected to be less at these locations due to the element design.

For very short conducting times, lifetime difference due to element shapes, sand and bounded sand will decrease in theory because of the delay in displacement. The maximum stress imposed depends mainly on thermal expansion caused by joule heating.

5. Conclusions

As fuses with sand fillers experience in pulsed currents, thermal buckling of the fuse element may take place during heating up. Because of cyclic nature, plastic deformation is generated.

Based on possible ageing mechanisms, a model has been developed to predict the number of current pulses which fuses withstand. Predictions and observations indicate that numbers of current pulses which fuses withstand decrease with the I^2t value of the current pulse. Reasonable agreement between predictions and experimental results has been found.

From statistical analysis, lifetimes of fuses are found to obey the Weibull distribution. If the power relation between I^2t of the pulsed current and the scale parameter λ is assumed, a linear relationship is achieved between the fuse lifetime N and the I^2t value of the pulsed current on a double log scale.

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