

SOME OBSERVATIONS ON THE ACCELERATED AGEING OF THICK-FILM RESISTORS

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Methods of accelerating the ageing of thick-film resistors (TFRs) have been explored, with encouraging results from experiments in which elevated temperature and damp heat were inflicted on TFRs. Consistent acceleration was obtained by increasing temperature, whether by storage or dissipation, the activation energies for thermal ageing of various resistor families lying in the range 0.5 eV–1.5 eV. Acceleration by humidity (*RH*) was also obtained, corresponding, for example, to a halving of life for a 20% increase of *RH*, some resistance changes being about an order of magnitude larger than those obtained at elevated temperature. The encapsulations played a dominant role in the degradation of resistors under both stress conditions.

According to the theories of conduction, degradation could occur because of reactions at conductive sites, causing corresponding changes in the conductivity and resistance versus temperature ($R(T)$) characteristics. Progressive degradation certainly did occur, as evidenced by the conformity of the ageing behaviour to a diffusion-type (time)^{1/2} dependence accompanied by shifts in the $R(T)$ characteristics. Some interpretation of the degradation has been possible by referring to an empirical model of the temperature dependence of resistance, but conflicting changes can be reconciled with the model only by postulating competing degradation mechanisms. The report covers an early stage of the work.

1. INTRODUCTION

In contrast with the abundance of test procedures for active semiconductor devices, methods of accelerating the ageing of thick-film resistors are not at all well established and even the prospect of them has been doubted. An attempt is accordingly being made to remedy this deficiency by the investigation, reported herein, of the behaviour of resistors of different value, composition and encapsulation from various manufacturers. Both the selection of the stress conditions and the interpretation of the results have been aided by a study of the prevailing theories of conduction in thick-film resistors.

2. CONDUCTION THEORY

Hill¹ and Forlani and Prudenziati² have shown that electrical conduction in thick-film resistors can be explained using the concepts of electron percolation and hopping between conductive sites, and a model has been proposed for the temperature dependence of resistivity ($\rho(T)$),³ from which the following expression has been derived:

$$\rho(T) = \frac{\sqrt{T}}{\beta} \exp\left(\frac{T_0}{T}\right)^{1/4} \quad (1)$$

in which β is a constant and T_0 is the activation temperature. Both are dependent on the density (N) of conductive sites and the decay constant (α) for the electron wavefunction in the resistor glaze. T is the absolute temperature. The characteristic dependence of resistance on temperature (hereafter called the “ $R(T)$ characteristic”), according to Eq. (1), is illustrated in Figure 1 showing the close conformity of the practical and theoretical characteristics normalised to the minimum point. The slope of the curve corresponds to the temperature coefficient of resistance (TCR), which is typically negative at low temperatures and positive at higher temperatures. The turning point (R_{\min}) occurs at $T_{\min} = T_0/16$. In common with others, we have found that the curves are characteristic of the resistivity, composition and fabrication of thick-film resistors, T_{\min} being displaced for resistors of different resistivity. Thus resistors may conveniently be characterised in “Groups” distinguished by their resistivity within “Families” of resistors having the same composition and fabrication.

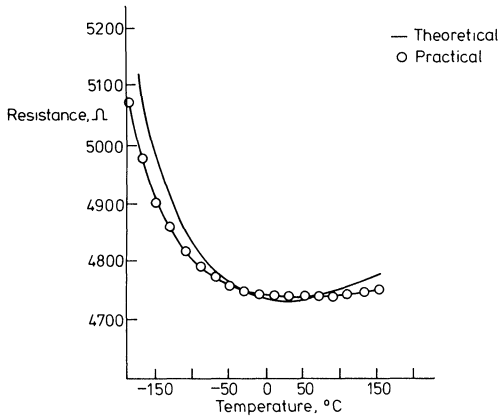


FIGURE 1 Practical and theoretical $R(T)$ characteristics for 4.7 kohm resistors.

According to the conduction model, changes in the characteristic for each group would occur if N or α altered. Thus mechanisms such as the diffusion of metal into the glaze, or oxidation or hydration following the ingress of water, should directly alter the density of conductive sites and give rise to corresponding changes in resistance and T_{\min} . On the other hand, the extension of microcracks in resistors could also alter their resistances, but without affecting T_{\min} . Whichever mechanisms prevailed, it was reasoned that they could be stimulated by conventional stresses such as temperature and humidity.

3. EXPERIMENTS AND OBSERVATIONS

Rectangular resistors in arrays of eight on alumina substrates made by five manufacturers using their standard ink formulations printed, fired and trimmed in the normal way, were supplied with and without encapsulation. The encapsulation was either a plastic coating or a ceramic lid stuck on with a plastic layer. The resistor values were 100 ohm, 4.7 kohm and 47 kohm, supplied either in separate arrays or in the same array. Whence it was expected that the results obtained would be representative of the wide spectrum of commercially available resistors, including the influence of the various encapsulations. Adopting the nomenclature suggested earlier, for this exercise, a "Family" would comprise all resistors from one source and a "Group" would comprise all resistors of one value from one source. The resistors were subjected to overstress by thermal storage or

maximum rated dissipation at elevated ambient temperatures or damp heat with bias. In summary, the most consistent response to all three stress conditions was the progressive increase of resistance with time, the rate of change differing with inks, resistor values and encapsulations, although some resistors remained remarkably stable and one group (in a somewhat fragile style of package) occasionally decreased in value.

3.1. Behaviour During Storage at Elevated Temperatures

These experiments were conducted at temperatures limited to 170°C for the encapsulated resistors. The range of changes obtained during 170°C storage of encapsulated 100 ohm resistors from five different sources is shown in Figure 2. The 90% confidence limits reveal increasing dispersions with increasing changes in resistance. As illustrated in Figure 3, resistors of different value from each source changed at different rates, and the sequence in which they changed differed from one source to another. These observations showed that no magnitude of resistor would universally represent worst-case degradation of all resistor families. So, acceleration factors were only determinable from the response of resistors from the same group. The consistent acceleration of resistance changes of one group of resistors during storage stress between 70°C and 170°C are shown in Figure 4. For this example, an activation energy of 0.7 eV has been calculated for resistance changes from 0.2% to 1.5%. Activation energies for other families of resistors appear to lie in the range 0.5 eV to 1.5 eV.

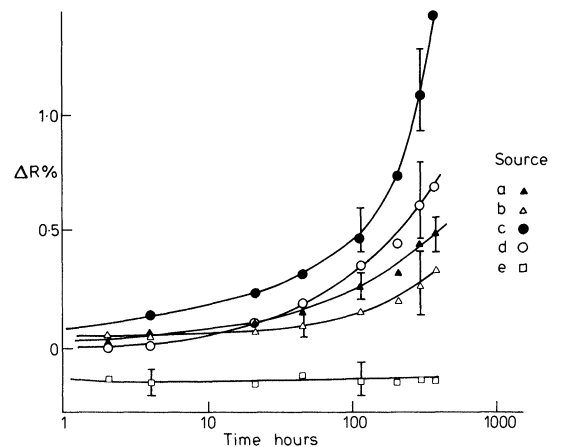


FIGURE 2 100 ohm resistors from five sources at 170°C.

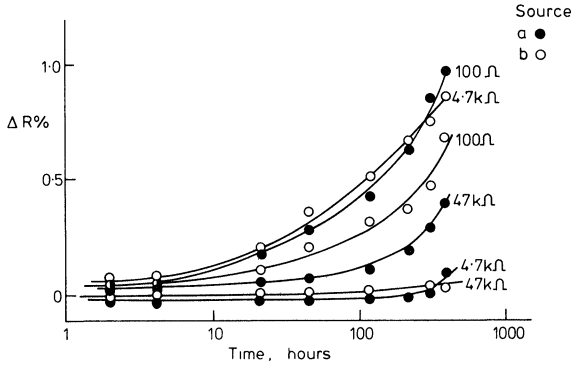


FIGURE 3 Resistors from two sources at 170°C.

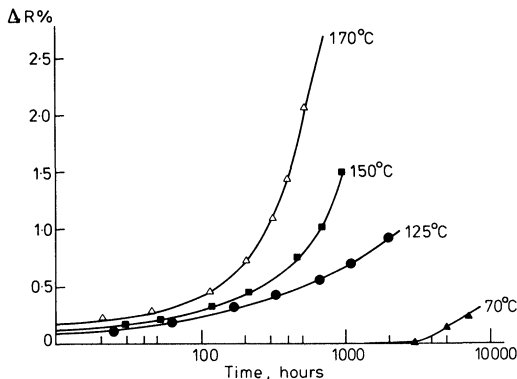


FIGURE 4 Response of 100 ohm resistors to thermal stress.

3.2. Behaviour During Dissipation at Elevated Ambient Temperatures

Dissipation can represent a different stress condition in resistors, not only because of the obvious presence of electric potentials and currents, but also because the confinement of the operating regions to narrow constrictions in the trimmed resistors results in non-uniform distribution of temperature.⁴ In order to compare the responses of the different families of resistors, a standard dissipation of 62 mW/mm² (for the total area of each resistor) was adopted for these tests. Taking into account the different trimming practices of the manufacturers, this value corresponded approximately to maximum ratings generally specified. The temperature generated by dissipation and the ceiling of 170°C for encapsulated resistors then imposed a corresponding limitation of 100°C on the ambient temperature applied to the networks. Observations from dissipation tests at 70°C and 95°C, plotted in Figure 5, show that resistor ageing

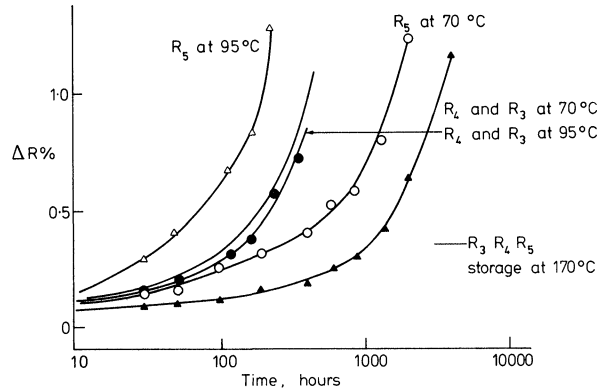


FIGURE 5 Response of 4.7 kohm resistors to dissipation of ambients of 70°C and 95°C.

followed a similar pattern to that obtained during storage. The behaviour at 95°C was largely indistinguishable from the response of resistors from the same group to storage at 170°C, which, taken together with an estimated temperature rise of about 75°C due to the dissipation in the network,⁴ strongly implied a consistent response to temperature, however applied. Significant and consistent anomalies were however observed in the more rapid ageing of particular 4.7 kohm resistors in the same location of every array of dissimilar resistors from one source, at both temperatures (Figure 5). The cause was subsequently found to be related to the presence of significantly different voltages on adjacent resistors.

3.3. Behaviour During Exposure to Damp Heat with Bias Applied

The hazards of moisture to active components are well documented^{5,6} and the study of conduction

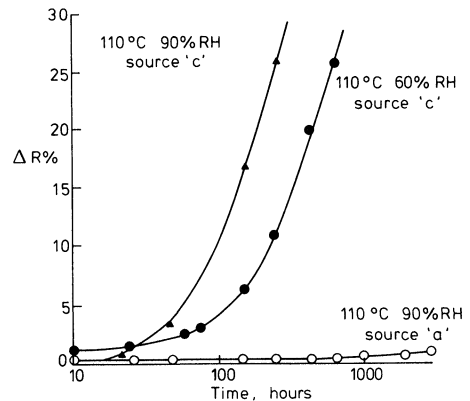


FIGURE 6 Responses of 100 ohm resistors to damp heat stress.

mechanisms shows that moisture could also induce changes in resistors. The experiments were conducted in autoclaves inflicting damp heat stress up to 110°C, 90% RH.⁷ Arrays with up to 50 V bias applied between adjacent resistors once again exhibited increasing resistance, but the changes were much greater, as illustrated in Figure 6 for two different humidities. The acceleration of ageing corresponds to a halving of life for a 20% RH increase in humidity at 70% RH for the example shown. Also shown in Figure 6 is an example of the remarkably stable behaviour of some families of resistors, which hardly changed in value after more than 6000 hours at high humidity.

3.4. Effect of Encapsulation

The foregoing illustrations have been of the behaviour of encapsulated resistors — shown not only because of their relevance to practical applications, but also because bare resistors changed much more slowly than their encapsulated counterparts, so that significant responses to many stress conditions are still awaited. Contrasting rates of change of bare and encapsulated resistors from two sources are illustrated in Figure 7. The exceptional decrease in resistance, mentioned in Section 3 was yet another and particularly dramatic illustration of the influence of encapsulation — which reversed the trend of behaviour of the bare resistors.

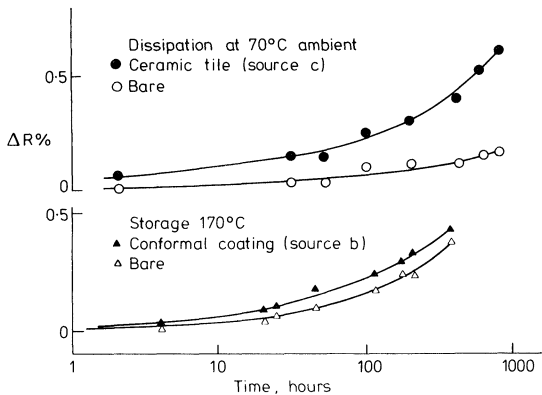


FIGURE 7 Responses of encapsulated and bare resistors of stress.

3.5. Analysis of Degradation

Changes in conduction arising from oxidation, hydration or metal migration are likely to be limited by the diffusion of the respective species. Consequent degradation of resistors should then conform

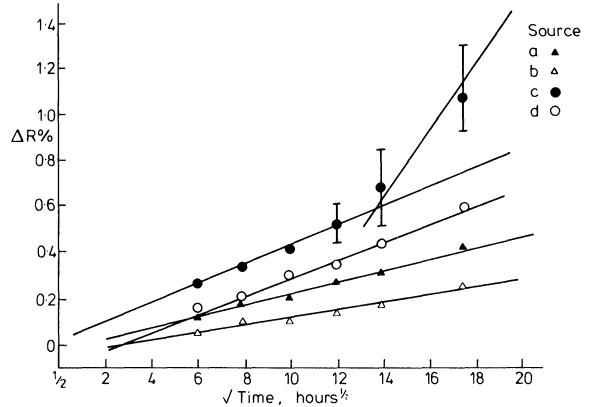


FIGURE 8 Resistance change versus √time at 170°C.

to a diffusion-limited time-dependence. Such conformity is illustrated in Figure 8, which shows that the ageing of most resistor families during thermal storage varied linearly with the square root of time ($\Delta R \propto t^{1/2}$). The generally observed change in slope when resistance changes exceeded about 1%, is consistent with a change in diffusion coefficient to a new value. An example of the larger changes obtained during humidity stress, replotted in Figure 9, shows that the linearity of the second line can extend beyond 20% change in resistance. Evidence that these mechanisms affected the conduction in the resistors was sought by examining the $R(T)$ characteristics. Shifts in the characteristics were certainly observed, but the changes were not always consistent and were consequently difficult to interpret. For example, increases in resistance of 100 ohm resistors after storage stress were accompanied by increases in T_{min} (Figure 10) which could correspond to a net decrease in density of conductive sites,

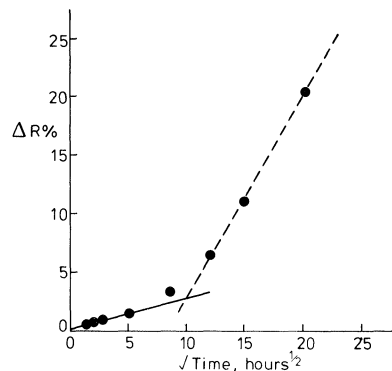


FIGURE 9 Resistance change versus √time at 110°C 60% RH.

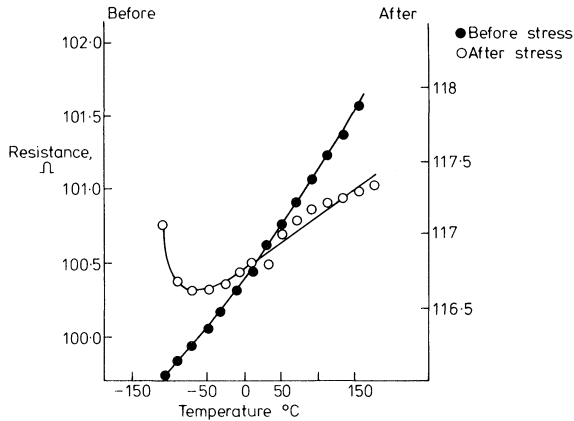


FIGURE 10 100 ohm resistors stored at 170°C.

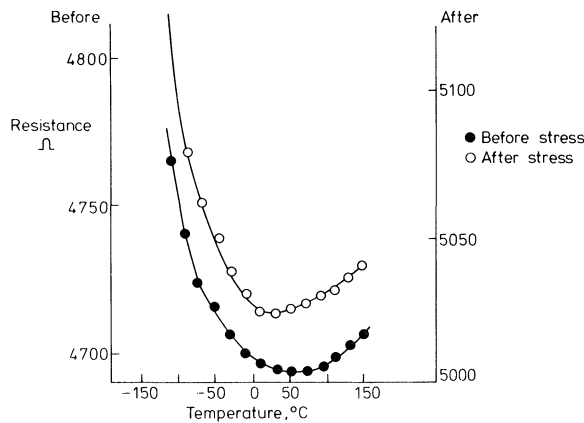


FIGURE 11 4.7 kohm resistors stored at 170°C.

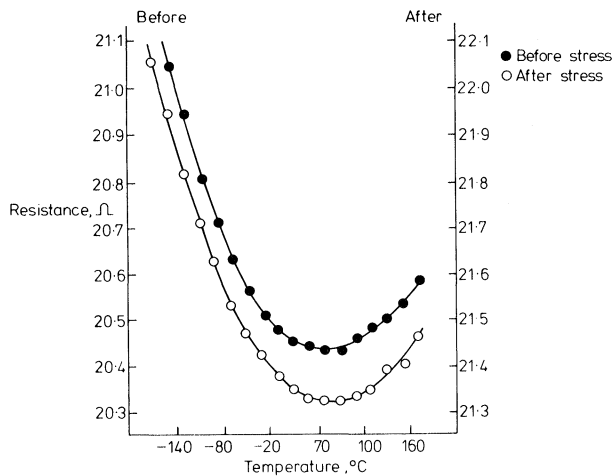


FIGURE 12 Resistors with induced cracks.

$R(T)$ characteristics before and after degradation.

[substitution for T_{\min} and ρ in the model, yields a net decrease in N of about 10^{21} m^{-3} corresponding to the changes shown in Figure 10], but the increase in resistance of 4.7 kohm resistors from the same family was accompanied by a conflicting, albeit modest, decrease in T_{\min} (Figure 11). To demonstrate that the effect of the stresses was not simply to extend microcracks, evidence is presented from an experiment outside the scope of the present paper, which nevertheless provided resistors with microcracks induced in them.⁴ As shown in Figure 12 the effect of the cracks was simply to increase the resistance, without otherwise disturbing the characteristic, which clearly contrasts with the shifts in T_{\min} caused by stress testing of the resistors.

4. DISCUSSION AND CONCLUSIONS

The most consistent pattern of behaviour observed during exposure to all of the stress conditions, was the progressive increase of resistance with time. The rates of change were found to vary not only between families of resistors, but also within each family of resistors. A significant influence on the behaviour of families of resistors was due to their encapsulation, which encourages the view that they would probably have been better without. The more stable behaviour was in fact obtained from resistors on thick substrates with thin plastic coatings. But such relatively short-term stability is not proof of long-term reliability — it just highlights the difficulty of proving reliability, because acceleration factors cannot be calculated until changes are obtained. The differences in response of the various resistors have certainly emphasized the need for obtaining reliability information only from the behaviour of resistors that are nominally the same in value and fabrication as those of interest. Responses obtained so far for similar resistors indicate that, if thermal ageing (storage or dissipation) obeys the Arrhenius relationship, $t = t_0 \exp(E_A/kT)$, then the activation energies (E_A) lie in the range 0.5 eV to 1.5 eV, and if damp heat ageing obeys the law $t = t_0 \exp(C[RH]^2)$, then C is about 10^{-4} . While the evidence of acceleration by these stresses is encouraging, and acceleration factors have been obtained for some groups of resistors, the general validity of the Arrhenius and humidity ageing relationships and the range of acceleration factors have to be confirmed by more tests now under way. The consistent anomaly observed because of the voltage sensitivity of resistors from one source, shows that yet another parameter can influence the ageing of thick film resistors.

The consistency of the degradation with a diffusion-limited mechanism, taken together with the shifts in T_{\min} of the $R(T)$ characteristics, certainly points to some progressive changes in the conduction properties of the resistors. Coincident increases of both resistance and T_{\min} are readily explained by the decrease of the density of conductive sites, but conflicting changes in resistance and T_{\min} may be reconciled with the theory only by postulating competing mechanisms. It is clear that more searching analyses of the structural and material properties of the resistors are necessary to assist the interpretation of these various changes.

In conclusion, it can be said that resistor ageing can be accelerated by temperature and humidity and that $R(T)$ characterisation has provided a useful insight into the mechanisms of ageing. These observations are from an early stage of the studies – the fuller picture will emerge as more results are obtained.

ACKNOWLEDGEMENTS

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