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SUMMARY

The surface insulation resistance (SIR) of double comb patterns deposited on FR-4, ceramic and flexible polyimide has been used to assess the efficacy of encapsulants (glob tops and dam and fill materials) to protect environmentally sensitive components from exposure to harsh conditions. The influence that solder resist has on the properties of the encapsulants has also been assessed using a proportion of FR-4 and ceramic boards. Six epoxies supplied by different companies have been studied together with a silicone and a polyurethane based encapsulant.

Continuous measurements of the SIR of both encapsulated and bare double comb patterns were made during exposure to atmosphere that alternates between dry (10%R.H.) and damp (90%R.H.) conditions as a function of increasing test temperature. This environmental conditioning enables the performance of the encapsulants to be simultaneously assessed as a function of both temperature and humidity.

CONTENTS

1 INTRODUCTION

The long term reliability of electronic devices is a key issue in todays markets. This places additional burdens on device manufacturers to ensure that their products function in a range of often aggressive environments e.g. automobile engine compartments. Curable plastics (encapsulants) are often used to selectively coat sensitive electronic components that could be damaged as a result of being exposed to, for example, high humidity, salt spray or fuel fumes. Encapsulants are available either as relatively high viscosity materials (glob tops) that are directly dispensed onto the component and its immediate viscinity or as ‘dam and fill’ products. A dam and fill product is composed of a high viscosity formulation which is used to produce a ring of material around the component (the dam) that is then filled with a low viscosity fill. Dam and fill materials are particularly successful in underfilling components due to the low viscosity of the fill component.

Typically manufacturers give relatively little guidance on how these materials perform under wide ranging environmental conditions. This introduces some uncertainty in selecting not only the appropriate type of encapsulant for a particular application but also deciding which manufacturers formulation is most appropriate. In this study we compare the performance of different manufacturers formulations, encapsulant chemistries on different substrates either with or without a resist coating.

1.1 THE MECHANISMS RESPONSIBLE FOR FAILURE OF CIRCUIT BOARD ASSEMBLIES

In service failure of chip scale packages or ball grid arrays can occur as a result of pad or wire bond corrosion or due to a breakdown in the surface insulation resistance (SIR) caused by current leakage. This current leakage consists of ions that flow between two conductors immersed in an electrolytic medium such as water. The driving force for the process is a difference in potential between the conductors. At its most severe the flow of positively charged metallic ions between two conductors can lead to the formation of dendrites on the cathode[1] that cause bridging. The amount of water within the board or glob top material immediately after manufacture is normally very little if the board has been suitably cleaned and dried. However this can change significantly with time especially if the board is exposed to damp atmospheres during service and if hydroscopic organic residues such as flux or cleaning agent surfactants are present. Organic residues can also contribute to ion flow within solids by forming soluble complexes with metal ions. Circuit corrosion can occur in the absence of an applied voltage if there is a difference in the electrochemical potential between two conductors. This difference in potential will cause ion migration and hence corrosion of the conductor. The subsequent build up of corrosion products can lead to bridging and shorting.

Exposing circuit boards to significant changes in temperature can result in damaged solder joints. Repeated thermal cycling of a junction formed between two materials that have different thermal expansion coefficients will generate stresses within the joint that may eventually cause it to crack. There is some evidence to suggest that this susceptibility to cracking can be marginally reduced by conformal coatings[2] and presumably encapsulants. However the efficacy of particular coatings or glob tops in this role will depend on their chemistry and how well they coat the soldered junction.

2 EXPERIMENTAL

2.1 BOARD DESIGNS AND MATERIALS

2.1.1 Selection of board materials and test patterns

The simple board design shown in Figure 1 comprises of four double comb patterns i.e. two differently sized squares of length 25 mm and 13 mm respectively and two circles of diameter 7.2 mm. The circular double combs although the same size have different connection rails. The guard rails shield the double comb patterns from noise. Each double comb pattern comprises of a 0.7 mm pitch gold over nickel track (350 μm track and 350 μm spacing).

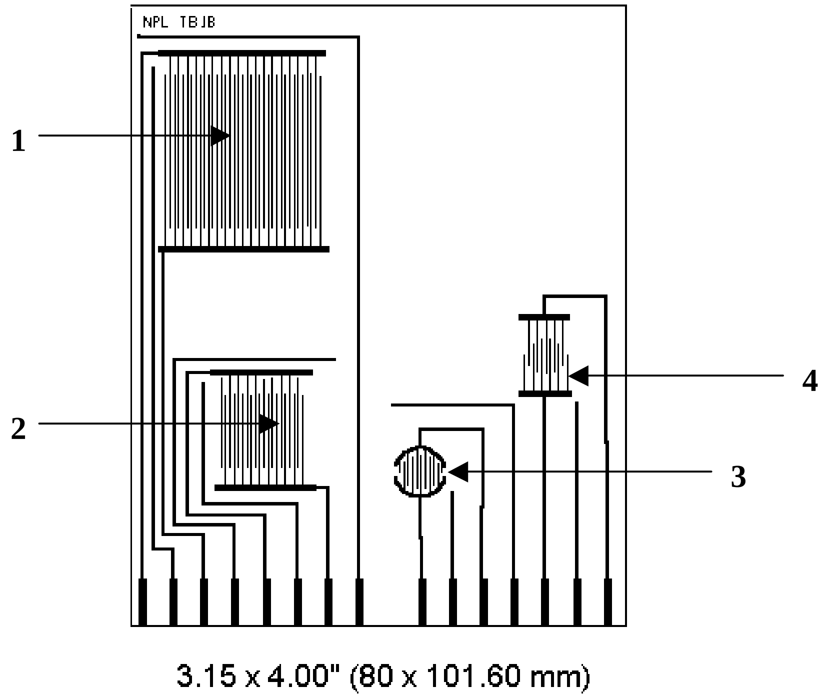

Figure 1: The test board comprises of four double comb patterns labelled 1 to 4.

FR-4, ceramic and flex (polyimide) were chosen as board materials. Before dispensing the glob top material the boards were cleaned using an IPA/deionised water mixture (75:25) for a period of approximately 10 minutes after which they were only handled by personnel wearing gloves. This procedure whilst not be representative of some industrial processes does eliminate board cleanliness as a potentially uncontrolled variable.

2.1.2 Encapsulant materials

Table 1 lists the encapsulants used in this study together with the cure schedules used. All the materials with the exception of UR1 and ER1 were stored at –40 ^{o}C prior to use. Both the glob top and dam and fill materials were dispensed using a Camalot M1818 single head dispenser.

Material code	**Type of material**	**Curing conditions**
ER1	Epoxy	RT 24 Hours
ER2	Epoxy	150 ^{o}C, 1 Hour
ER3	Epoxy	150 ^{o}C, 1 Hour
ER4	Epoxy	150 ^{o}C, 1 Hour
UR1	Urethane	RT 24 Hours
DF1	Epoxy	150 ^{o}C, 1 Hour
DF2	Epoxy	150 ^{o}C, 1 Hour
SR1	Silicone	150 ^{o}C, 1 Hour

Table 1: Details of the encapsulant materials and their curing cycles.

Using a machine to dispense the encapsulants ensures that repeatable volumes of material can be accurately dispensed over prescribed regions of the boards. Care was taken to ensure that the double comb patterns were completely covered by the encapsulants as shown in Figure 2. A single head was used to dispense all the materials including the 'dam and fill' encapsulants – the 'dams' were dispensed and cured prior to adding the 'fills'. All the materials were cured at 150 ^{o}C for a period of at least 1 hour with the exception of UR1 and ER1. Significant differences in the dimensions of the cured glob tops occurred with different manufacturers products. This variation is attributed to differences in the surface tension of the encapsulant on different substrates and in the solid content of different formulations.

Table 2 : Adhesive bond failures for encapsulated double comb patterns deposited on to ceramic substrate that occurred immediately after curing.

Time of failure	Encapsulant type	Identity of detached combs
After Cure	DF2	1
	SR1 + resist	1,2,3,4

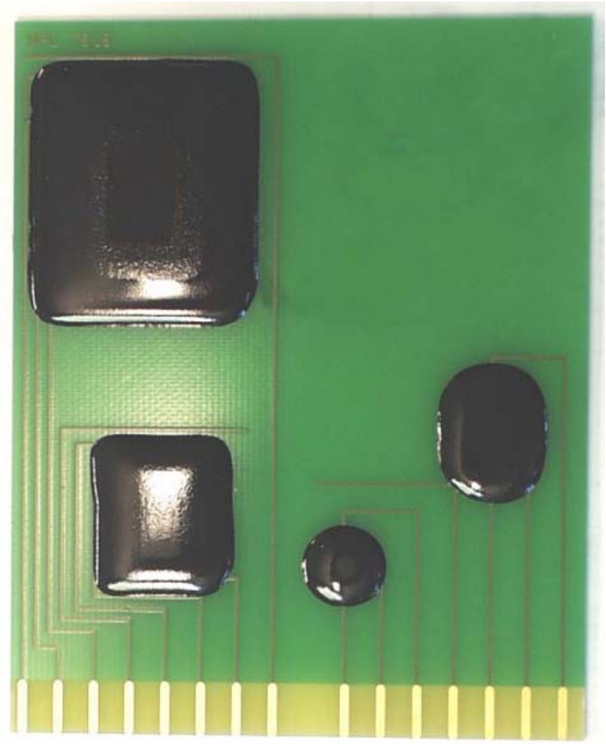

Figure 2 : An example of a urethane based glob top dispensed on to a ceramic board coated with solder resist. Note that the glob tops not only cover the double comb areas but also their immediate viscinity i.e. the solder resist coated ceramic.

Problems were experienced in using some materials dispensed on to ceramic test boards. Coating SR1 in particular tended to detach itself from resist coated ceramic boards as they were cooled after being removed from the high temperature curing oven as shown in Table 2. The large double comb 1 was particularly susceptible to delamination which is presumably due to the difference in thermal expansion coefficients between it and the ceramic substrate. There is also a suggestion that bond strengths may be weakened in the presence of the resist although this needs to be confirmed by further work. It should be noted that the resist coating applied to the boards does not cover the double comb patterns, the glob top material is therefore only in contact with a small amount of resist.

2.2 MEASUREMENTS OF SURFACE INSULATION RESISTANCE

2.2.1 Test conditions

Exposing the test boards to alternating wet and dry environments over a range of temperatures enables the performance of different glob tops to be assessed and compared.

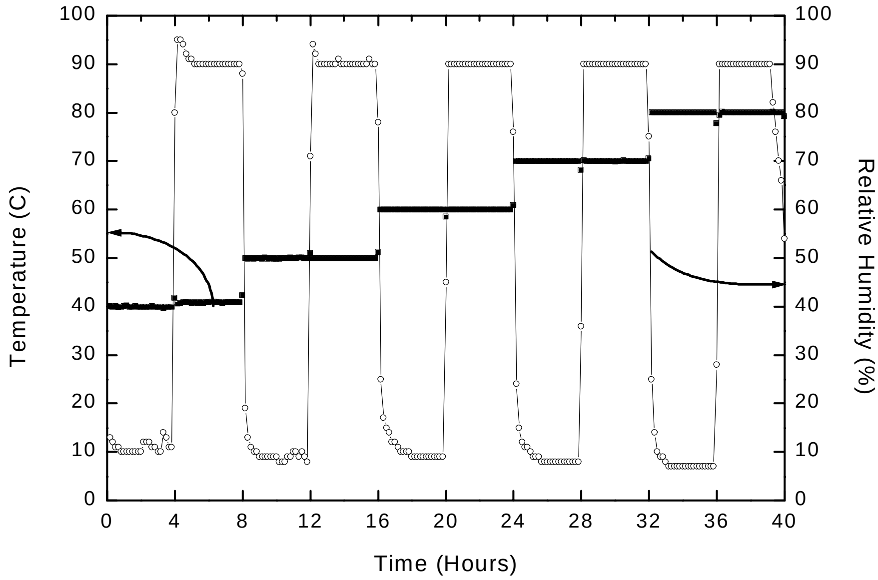

Figure 3 : The temperature/humidity profile.

A typical measured profile for humidity and temperature during a test is shown in Figure 3. The humidity is cycled over a two hour period from 10% RH to 90% RH and is superimposed on to a stepped temperature profile where each step is maintained for a period of four hours. The temperature and humidity conditions within the environmental chamber were monitored by wet and dry platinum resistance thermometers.

During the test period a +50 V biased voltage was continuously applied across the double comb patterns that were held in an upright position in the conditioning chamber. A 10^6 **Ω** limiting resistor was included in each measurement channel to preserve any dendrites that formed.

2.2.2 Data collection

A Concoat AutoSIR was used to measure the SIR of the test boards every 15 minutes during the 44 hour test period. This instrument has a current sensitivity of approximately 1 x 10^{-11} A.

3 RESULTS AND DISCUSSION

3.1 VISUAL APPEARANCE

Whilst the opacity of the encapsulants prevents direct visual inspection of the boards for signs of corrosion it is possible to look for evidence of delamination or cracking. Delamination of the encapsulant even if incomplete could provide an easy route for moisture ingress and an explanation for poor SIR performance.

3.2 THE SIR OF CONTROL BOARDS

Figure 4 shows the time dependence of log SIR for double combs deposited on a bare ceramic board. Clearly the behaviour of log SIR mirrors the change in humidity of the test environment. Recovery of log SIR occurs over a very short timescale to values in excess of the measurement capability of the test equipment (approximately 10^{13} Ohms). The ability of the board SIR to recover during exposure to low humidity decreases with increasing temperature. This result is not unexpected due to the additional quantity of water contained in the atmosphere at these temperatures is presumably reflected as an increase in the moisture content of the encapsulated boards. The variation in log SIR between different patterns is a reflection of the different comb areas (as discussed in section 3.2.2) and a measure of noise in the measurement system.

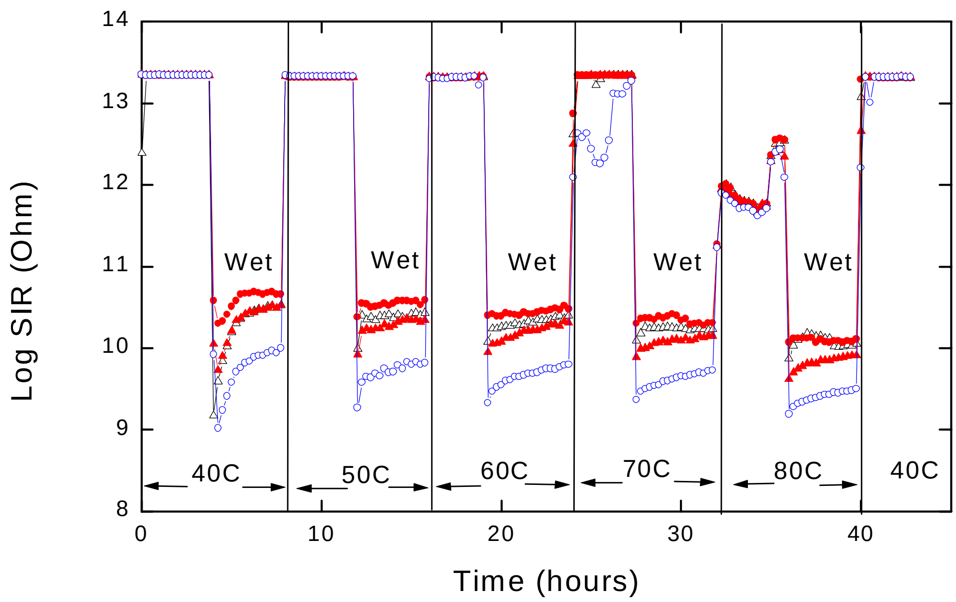

Figure 4 : Log SIR for bare double combs deposited on to a ceramic substrate reflects the changes in humidity that occur with each temperature increment. The magnitude of log SIR depends on the area of the double comb (❍ = pattern 1, ▲ = pattern 2, △ = pattern 3, ● = pattern 4). The damp phase of the humidity cycle is indicated in this and subsequent figures.

Figures 5 and 6 show the SIR behaviour of FR-4 and flex respectively. The lowest measured SIR values correspond with the large double comb pattern (1). On the basis of figures 4, 5 and 6 it is evident that the SIR of FR-4 board is greater than that of ceramic or flex over the entire temperature range.

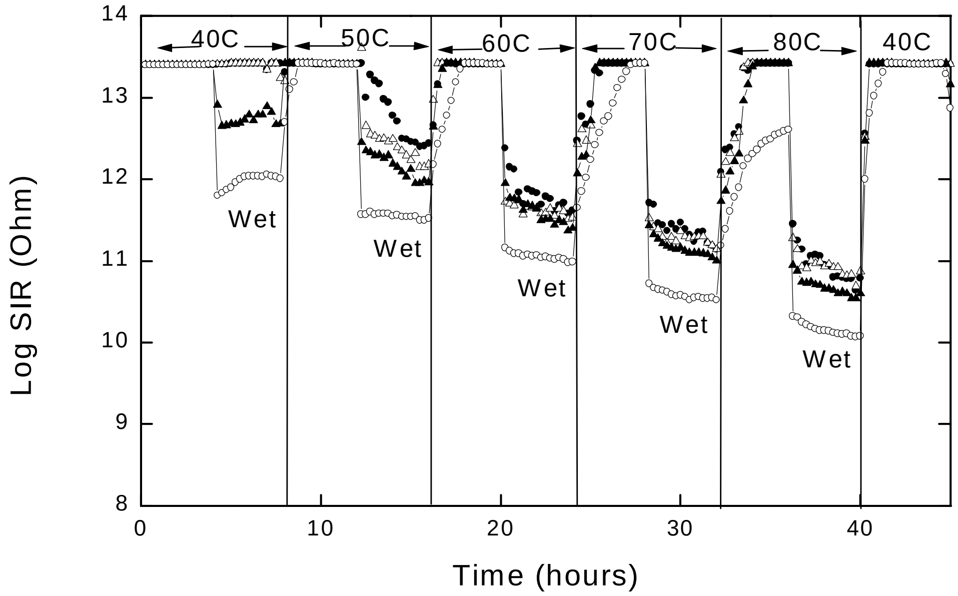

Figure 5 : Log SIR for bare double combs deposited on to FR-4 reflects the changes in humidity that occur with each temperature increment. The magnitude of log SIR depends on the area of the double comb (❍ = pattern 1, ▲ = pattern 2, △ = pattern 3, ● = pattern 4).

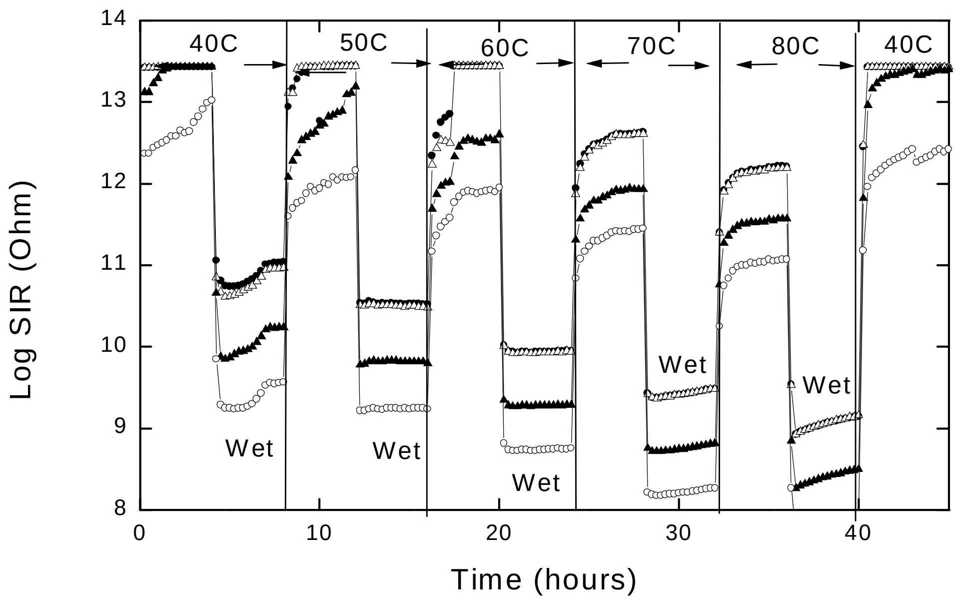

Figure 6 : Log SIR for bare double combs deposited on to flex (polyimide) reflects the changes in humidity that occur with each temperature increment. The magnitude of log SIR depends on the area of the double comb (❍ = pattern 1, ▲ = pattern 2, △ = pattern 3, ● = pattern 4).

A plot of log SIR versus time for encapsulated double comb patterns is shown in Figure 7. Again the peaks and troughs seen in the plot correspond to the damp and dry phases of the humidity cycle analogous to the bare control boards. Note that the SIR rapidly falls during the damp phase of the humidity cycle indicating that this particular material is not acting as a moisture barrier for temperatures in excess of 40°C. This behaviour is common to a number of urethanes, silicones and acrylic materials as shown in Appendix 2.

3.3 COMPARISONS OF SIR DATA

Comparisons of the SIR behaviour of different control boards and encapsulants can be simplified by following a simple graphical procedure. Since details of the procedure have been previously described[4] only a brief introduction will be presented here. The technique involves plotting the average or mid-point value for log SIR measured during the damp phase of the humidity cycle against temperature. In general the data for temperatures in excess of 40°C fall on a straight line. This can be modelled using a simple least-squares procedure to give an intercept and a slope. The slope is a measure of the temperature dependence of log SIR and it can be used with the intercept to predict the value of log SIR at any temperature under 90% humidity conditions. Arbitrarily we have chosen to compare the performance of different encapsulants using the predicted value for log SIR at 50°C although any temperature would suffice.

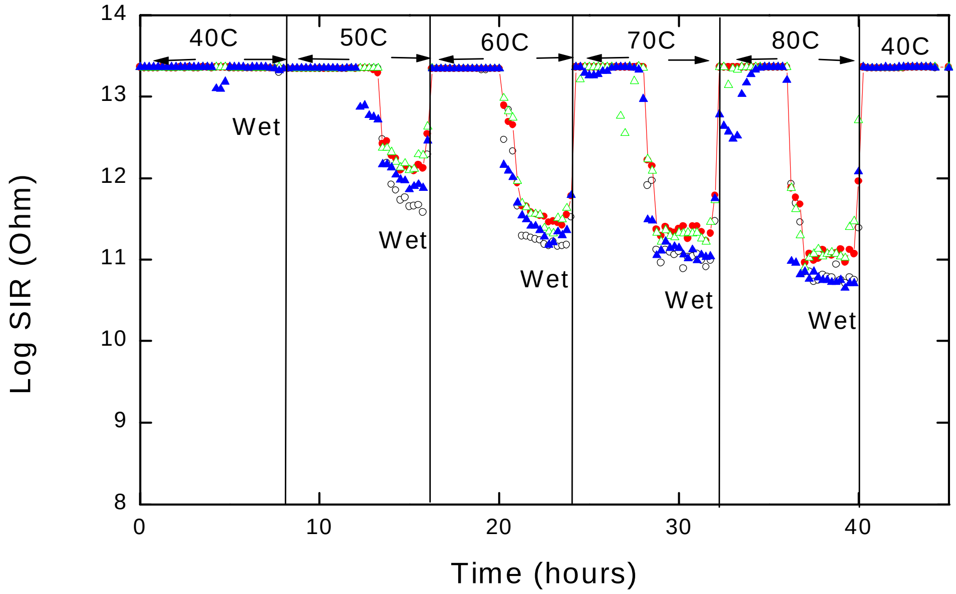

Figure 7: A typical plot of log SIR versus time obtained for a glob top (epoxy based) deposited on to a ceramic board. The environmental conditions are indicated on the figure. The humidity cycles between 10% RH (the first two hours at each temperature) and 90% RH (shown as 'wet'). (❍ = pattern 1, ▲ = pattern 2, △ = pattern 3, ● = pattern 4).

3.3.1 The effects of different substrates on SIR

Figures 8, 9 and 10 show how the predicted SIR at 50°C for different encapsulants varies with ceramic, FR-4 and flex substrates respectively. It is apparent from the figures that the SIR of the encapsulants falls by approximately two decades when they are dispensed on to flexible polyimide compared with the same materials dispensed on to ceramic or FR-4 with the possible exception of encapsulants ER2 and ER4. In comparison with figures 8 and 9 the data in figure 10 shows a strong tendency to fall with increasing pattern area. The SIR of encapsulants deposited on to both ceramic and FR-4 appears to be independent of the nature of the substrate and the area of the double comb pattern. This behaviour is probably due to the inability of the AutoSir equipment to accurately measure the very high values of SIR exhibited by the encapsulants dispensed on to these boards.

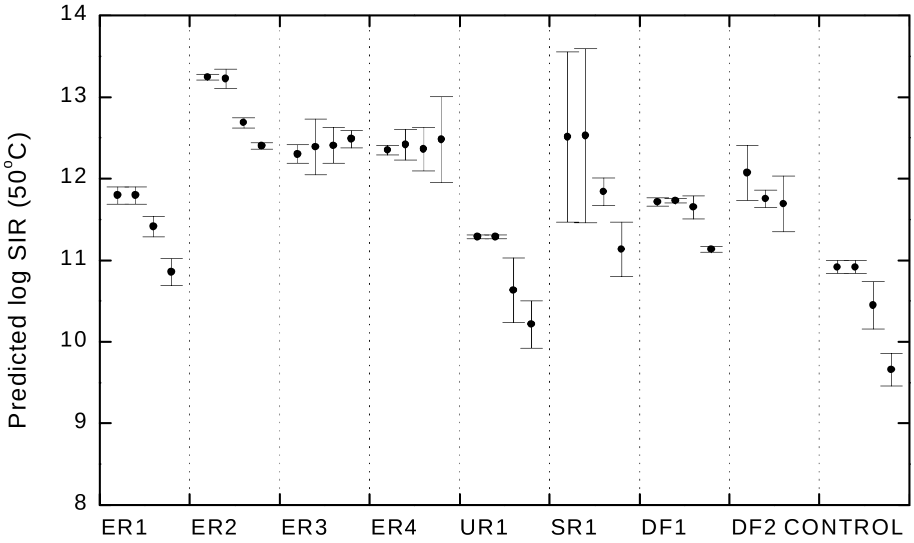

Figure 8 : A plot of the predicted value for log SIR at 50°C for different types of encapsulant deposited on to a ceramic substrate (the control). The four points per material represent the data from combs 4 to 1 in this sequence. Each datum is an average value from two identical patterns on different boards.

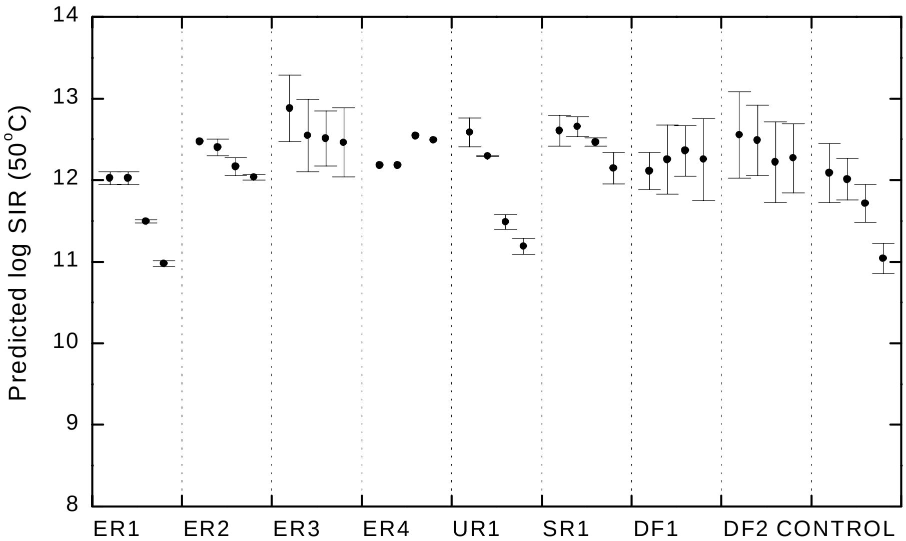

Figure 9 : A plot of the predicted value for log SIR at 50°C for different types of encapsulant deposited on to FR-4 substrate (the control). The four points per material represent the data from combs 4 to 1 in this sequence. Each datum is an average value from two identical patterns on different boards.

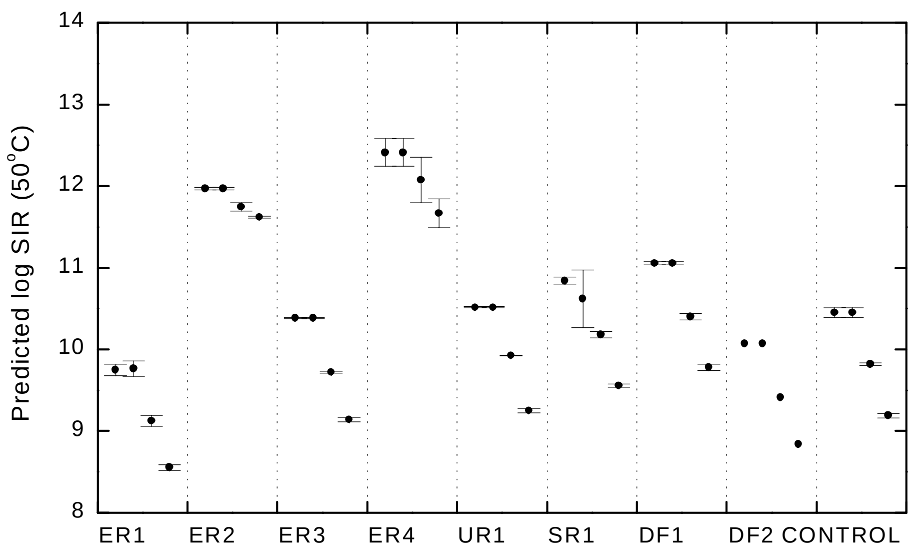

Figure 10 : A plot of the predicted value for log SIR at 50°C for different types of encapsulant deposited on to a flexible substrate (the control). The four points per material represent the data from combs 4 to 1 in this sequence. Each datum is an average value from two identical patterns on different boards.

Coating FR-4 and the ceramic boards with a solder resist has a negligible effect on the SIR behaviour of the bare board or encapsulated patterns (see Appendix 1 for further details). This result is not unexpected given that the resist does not cover the double comb patterns.

Figures 11, 12 and 13 compare the temperature dependence of log SIR for different encapsulants with that of the control boards. The temperature dependence data are, as previously described, a measure of how log SIR changes with temperature. High negative values of the temperature dependence are indicative of low SIR values at elevated temperatures that may be a cause for concern. The similarity of the data shown in figures 11 and 12 suggest that there is little difference in the performance of the encapsulants on different substrates. However it is possible that there is some distortion on these data due to the difficulty in measuring the very high values of log SIR that occur even at high temperatures. There is more variation in the data shown in figure 12 for the flexible substrate indicating that encapsulants ER4 and DF1 are more sensitive to temperature than the other materials used in this study. The temperature dependence of log SIR appears to be insensitive as expected to differences in pattern area.

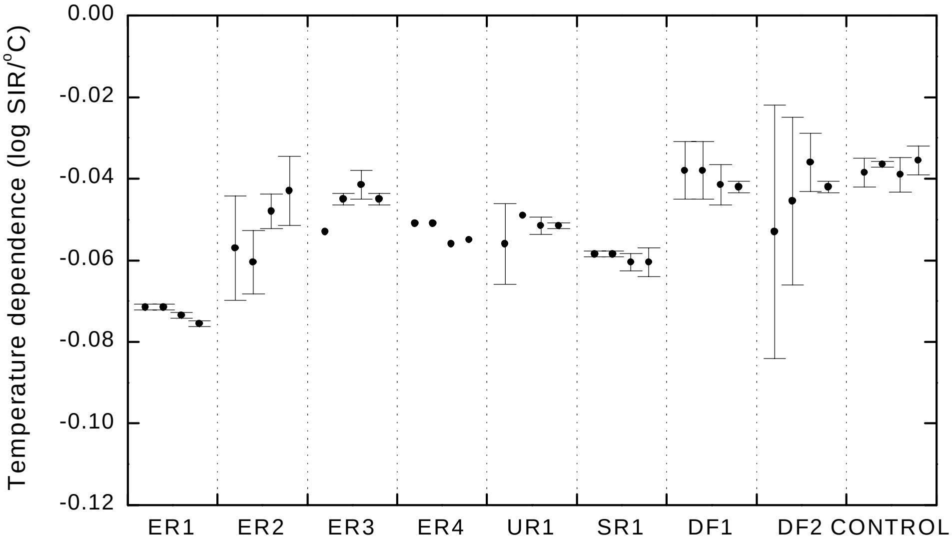

Figure 11. The temperature dependence of log SIR for FR-4 board (the control) under damp conditions. These are linked with the predicted log SIR values shown in figure 9

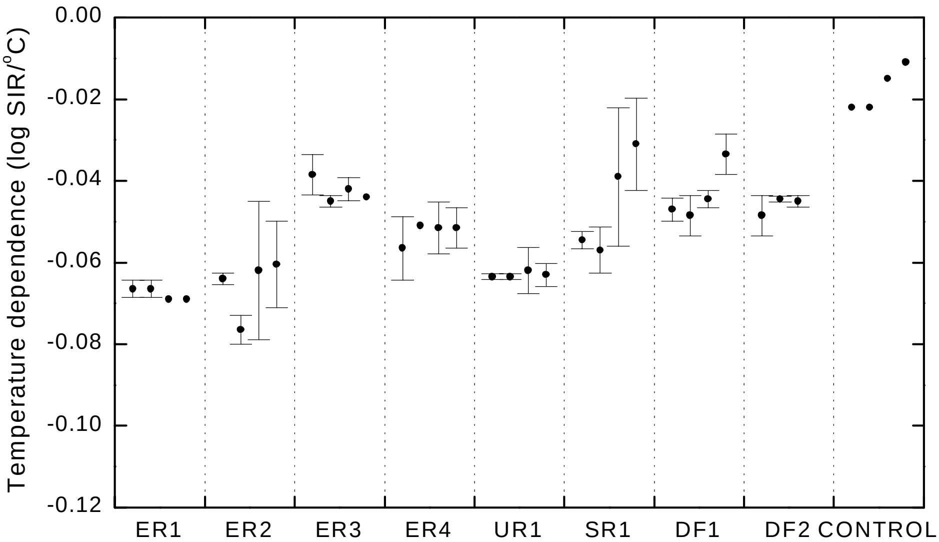

Figure 12. The temperature dependence of log SIR for ceramic board (the control) under damp conditions. These are linked with the predicted log SIR values shown in figure 8

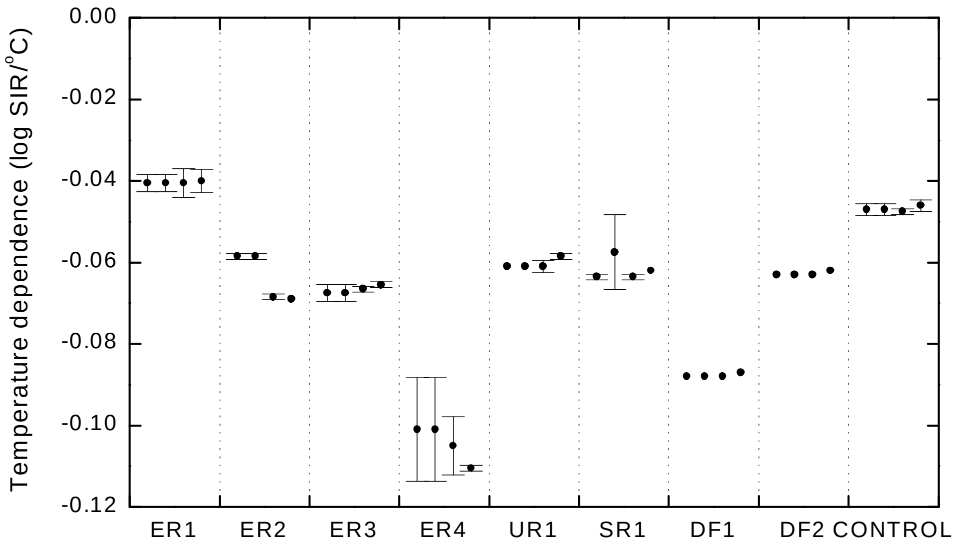

Figure 13. The temperature dependence of log SIR for flexible polyimide (the control) under damp conditions. These are linked with the predicted log SIR values shown in figure 10.

3.3.2 Scaling of SIR with comb pattern area

The ratio of double comb patterns 1 – 4 based on their respective areas is 1 : 0.253 : 0.052 : 0.052. Figure 14 shows a plot of the pattern ratios for bare boards with respect to the SIR data for pattern 1. These data are based on the predicted values of log SIR at 50°C. From figure 12 it is apparent that there is a reasonable agreement between the experimentally obtained ratios with that based solely on pattern area. This approach can be used as a tool to explore the quality of SIR data obtained from encapsulated patterns. Unusual ratios or spurious points are indicators of poor data, unmeasureably high values of SIR or perhaps encapsulant damage.

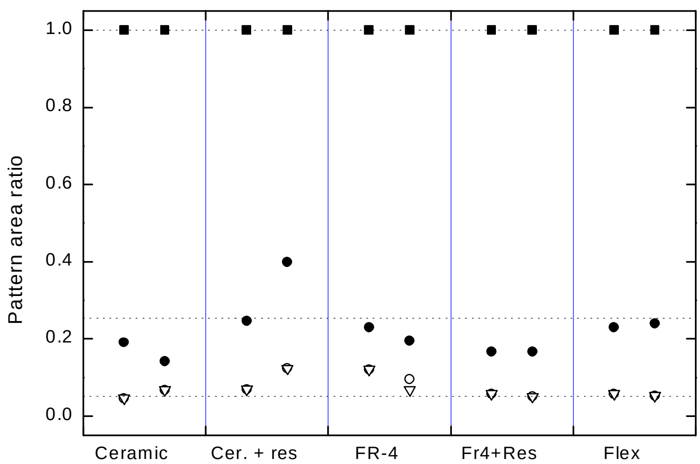

Figure 14: A comparison of the pattern ratios based on the predicted values of log SIR at 50 °C for bare patterns on different substrates. (■ = pattern 1, ● = pattern 2, ∇ = pattern 3, ❍ = pattern 4).

3.3.3 Encapsulant performance and SIR

Whilst we have compared the performance of different encapsulants as a function of temperature it is not immediately apparent how these different coating actually affect SIR at elevated temperatures. Plotting the predicted SIR behaviour of different encapsulants as a function of temperature provides an easily assimilated comparison that can be used to select materials as shown in Figure 15. In this figure it is apparent that the SIR of encapsulant ER1 despite having a relatively low SIR value at 50°C may be more suited to certain applications because its SIR is relatively stable with temperature in contrast to material ER4 which shows a three decade change.

3.4 MEASUREMENT ISSUES

The small circular double combs have a significantly higher SIR than the larger rectangular patterns because of their size. This disparity can lead to measurement problems using a relatively low voltage of 50 V. Whilst this problem can be reduced by increasing the applied voltage there is evidence to suggest that the results will not be representative of the boards performance under lower operating voltage conditions[3].

Some glob top materials appear to be relatively water resistant. The SIR of the material shown in Figure 16 remains almost independent of changes in humidity but shows an expected progressive decrease with increasing test temperature. It could be argued that this apparent insensitivity to moisture is due to the relatively short exposure times to high and low humidities. However the data shown in Figure 17 clearly shows that the SIR reaches a stable values after exposure to 85% RH at 85 °C within a period of approximately 30 minutes, although these conditions are more likely to induce the flow of ions.

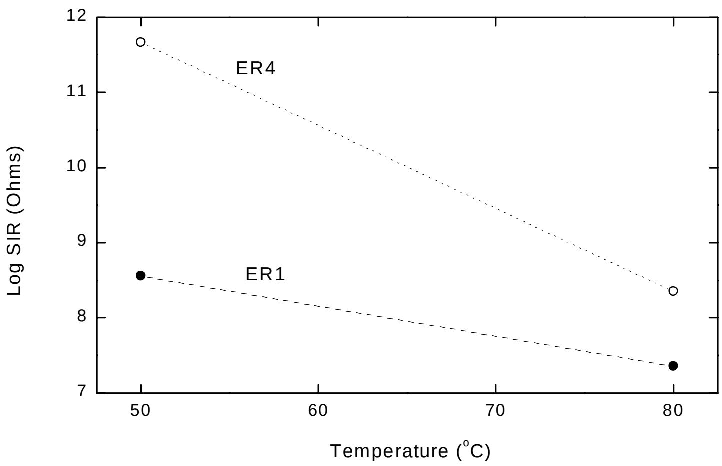

Figure 15: A comparison of the predicted log SIR behaviour of encapsulants ER1 and ER4 on a flexible substrate as a function of temperature under humid conditions.

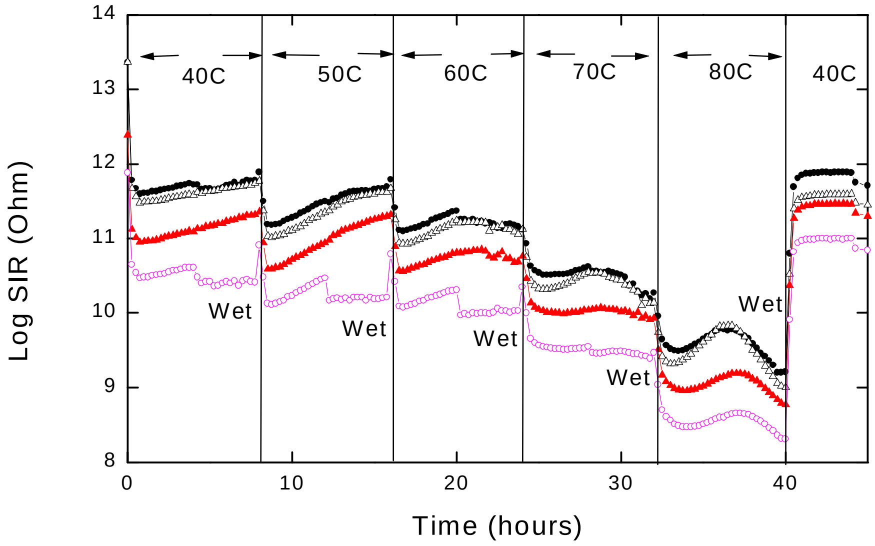

Figure 16 : ER1 deposited on to ceramic appears to be 'moisture resistant' i.e insensitive to changes in humidity over a relatively wide temperature range. (❍ = pattern 1, ▲ = pattern 2, △ = pattern 3, ● = pattern 4).

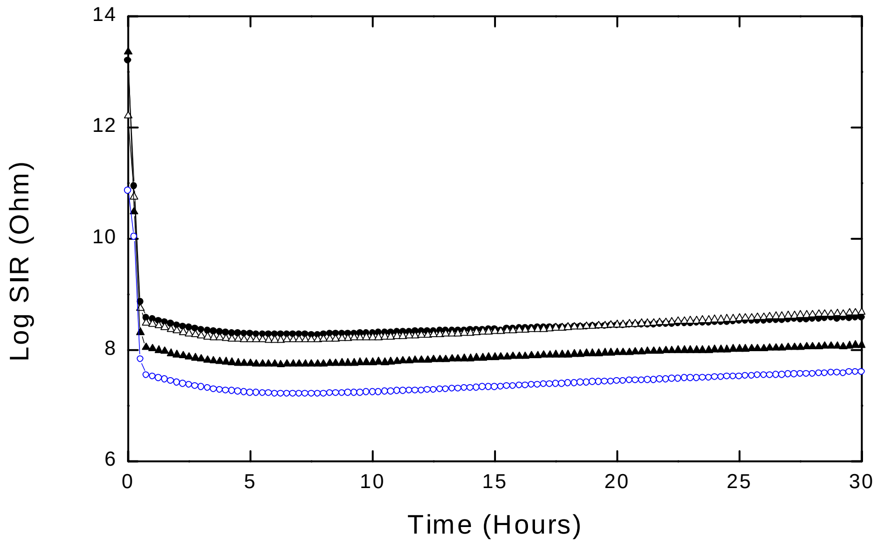

Figure 17 : The SIR of the ER1 deposited on to ceramic rapidly reaches a stable value within approximately 1 hour after exposure to 85 %R.H. and 85^{o}C. (❍ = pattern 1, ▲ = pattern 2, △ = pattern 3, ● = pattern 4).

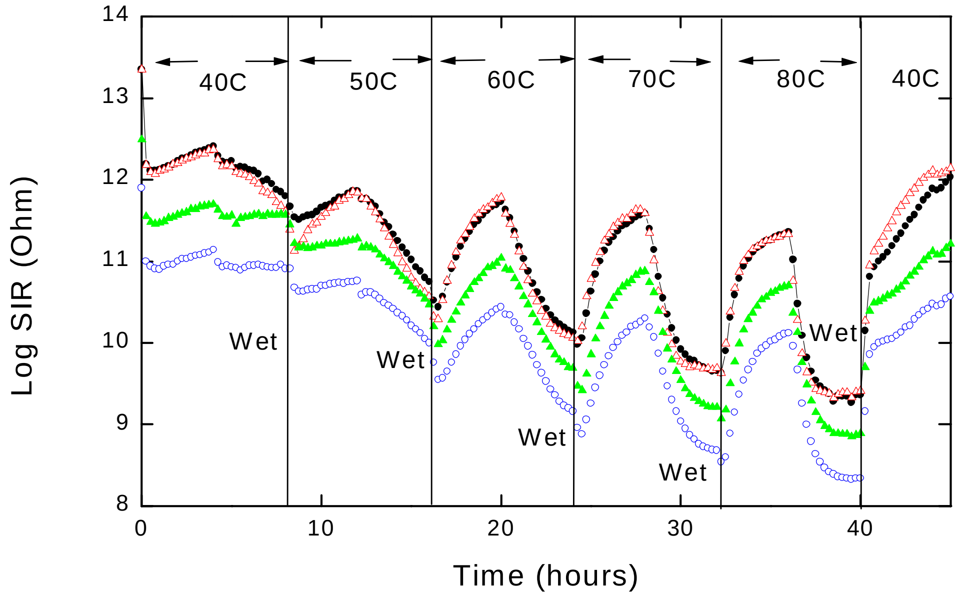

Figure 18 : UR1 deposited on ceramic behaves as a 'semipermeable' material becoming increasingly sensitive to changes in humidity with increasing temperature. (❍ = pattern 1, ▲ = pattern 2, △ = pattern 3, ● = pattern 4).

Figure 18 shows an example of a glob top material that appears to be 'semipermeable' to water at higher temperatures. At 40 ^{o}C the large rectangular combs are insensitive to increasing the humidity from 10 to 90% RH.. At higher temperatures the change in log SIR during exposure to dry or damp environments becomes increasingly more apparent.

However the rate at which log SIR changes after a change in the atmospheric humidity is much slower than that for the material shown in figure 7.

The procedure described in section 3.3 can be applied to materials that show similar behaviour to the examples shown in figures 16 and 18. However it must be recognised that the temperature dependence of log SIR will not be as accurate as that for the material shown in figure 7.

4 CONCLUSIONS

In principle the SIR of encapsulated comb patterns can be used to assess the performance of different types of material or different manufacturers formulations exposed to a variable humidity/temperature environment. However in practice the SIR of the encapsulated double comb patterns deposited on to FR-4 or ceramic substrates can exceed the measurement capability of commercially available test equipment. The results of this study show that encapsulants are effective in maintaining high values of SIR even under harsh conditions (90% RH, 80 ^{o}C) over the timescale of the environmental conditioning. Encapsulants deposited on to FR-4 or ceramic substrates tend to out perform the same materials deposited on to flexible polyimide in terms of both the absolute level of SIR and its temperature dependence under damp conditions. The latter is more severe for polyimide than for FR-4 or ceramic although the data for the latter two materials may have been distorted because of the difficulty in measuring very high SIR values. The presence of a solder resist appears to have no effect on the temperature/humidity performance of log SIR although it should be noted that the resist does not coat the double pattern test areas.

In practical terms all of the different types or formulations of encapsulant appear to perform equally well, particularly on solid substrates when exposed to the environmental profile described in this report. Encapsulants ER2 and ER4 appear to out perform other encapsulants when deposited on to flexible polyimide.

5 ACKNOWLEDGEMENTS

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3 L. Zou and C. Hunt,’ The effect of test voltage, test pattern and board finish on surface insulation resistance (SIR) measurements for various fluxes’, National Physical Laboratory Report, CMMT (A) 222, September 1999.

4 P.E. Tomlins and L.Zou, ‘A method to quantify the SIR of glob tops exposed to different temperature/humidity environments’, National Physical Laboratory Report, CMMT (A) 290, September 2000.

APPENDIX 1 : THE SIR BEHAVIOUR OF RESIST COATED BOARDS

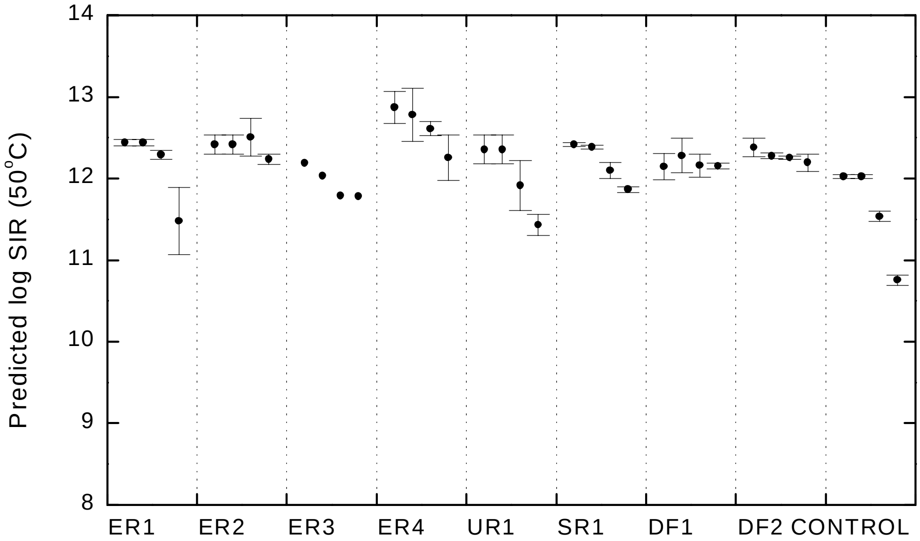

Figure A1: The dependence of log SIR on temperature and humidity for **resist coated FR-4** (the control). The key to the data is given in the legend to Figure 8.

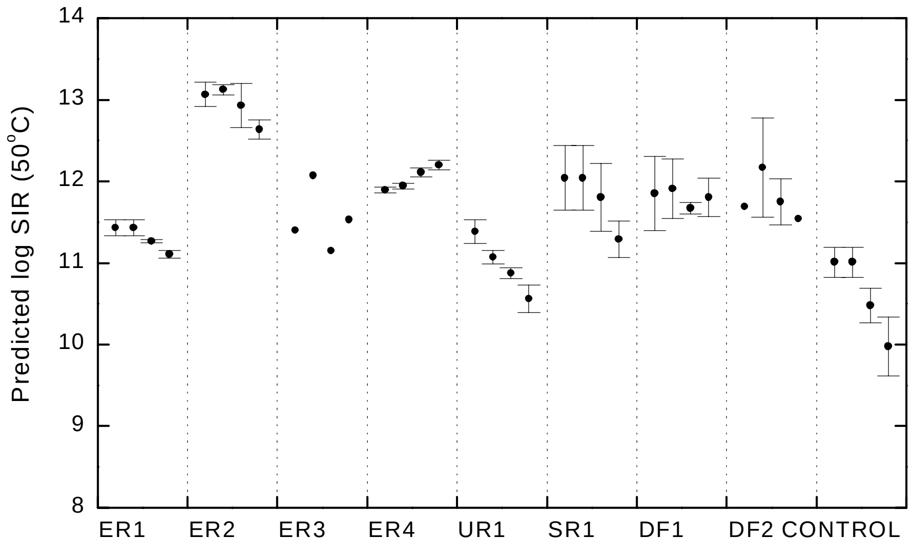

Figure A2 : The dependence of log SIR on temperature and humidity for **resist coated ceramic** (the control). The key to the data is given in the legend to Figure 8.

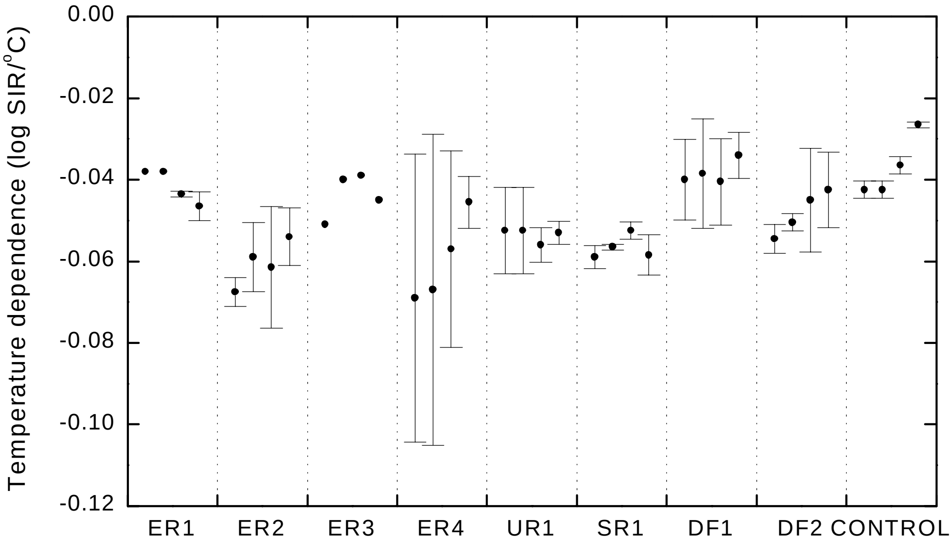

Figure A3 : The temperature dependence of log SIR under damp conditions for **resist coated FR-4** (the control). The key to the data is given in the legend to Figure 8.

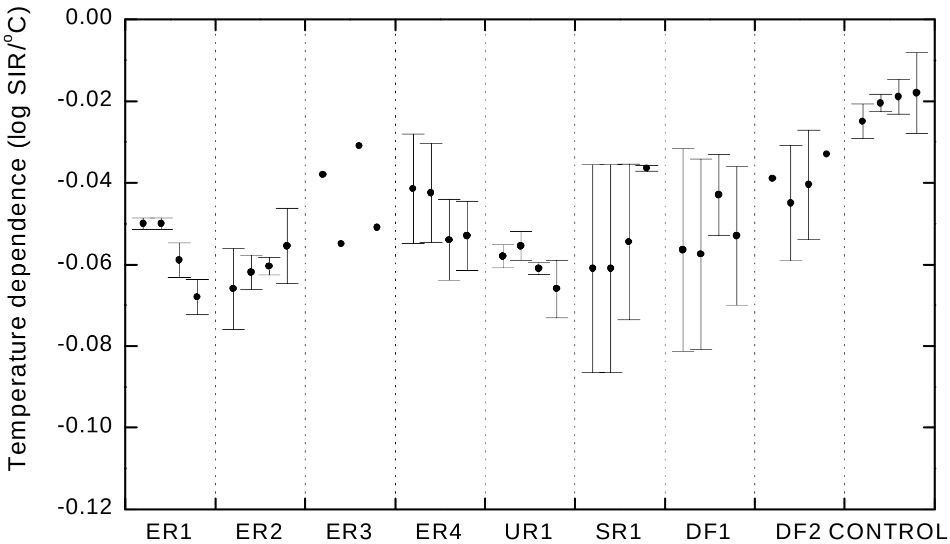

Figure A4 : The temperature dependence of log SIR under damp conditions for **resist coated ceramic** (the control). The key to the data is given in the legend to Figure 8.

APPENDIX 2 : PLOTS OF LOG SIR VERSUS TIME FOR DIFFERENT GLOB TOP AND BOARD MATERIALS