HUMIDITY ACCELERATION FACTOR FOR PLASTIC PACKAGED ELECTRONIC DEVICES

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SUMMARY

Failure mechanisms associated with the effects of humidity on plastic packaged devices are briefly reviewed. Relevant experimental and theoretical work on these failure mechanisms is then considered, pointing to an incomplete understanding as to why relative humidity is the appropriate variable, along with temperature to use in acceleration factor models. The BET equation (Brunauer, Emmett and Teller), is invoked to provide a theoretical underpinning to the use of relative humidity in such acceleration factor models. The BET equation provides such a connection by relating surface concentration of water to vapour pressure of water. Using the BET equation as a starting point, we derive a relation between surface concentration of water and relative humidity that has no explicit temperature dependence.

We then consider a simple kinetic model for a corrosion reaction leading to failure. The result is an acceleration factor that is a typical Arrhenius form, multiplied by a simple function of relative humidity. This form is similar to other power-law acceleration factor models that have been developed empirically. Now a physical derivation is offered as a theoretical basis for power-law models of the effects of humidity on plastic packaged device reliability.

INTRODUCTION

Plastic packages for electronic devices have long been considered a cost-effective alternative to hermetically sealed packages. However, lingering concerns about the difference in reliability between plastic packaged devices and hermetically sealed devices have prevented plastic packaged devices from supplanting hermetically sealed devices in higher reliability applications. As plastic packaging technology has evolved over the years, these concerns have been reduced to the point that plastic packages are used commonly in all but the highest reliability applications. Ultra-high reliability systems may be compromised by the failure mechanisms that are primarily associated with plastic packaged devices, even though plastic package technology has improved enormously.[1, 2] There is still resistance to the use of plastic packaged devices from the more conservative customers of moderate to high reliability systems. In this paper, the wear-out failure mechanisms endemic to plastic packaged devices are briefly reviewed. Relevant experimental and theoretical work on these failure mechanisms is then considered, leading to the recommendation that an Arrhenius form, supplemented by a function of relative humidity, be considered as an acceleration factor to use in reliability estimation.

FAILURE MECHANISMS

As the title of this paper suggests, it is primarily the effect of humidity that differentiates plastic package device reliability from that of hermetically sealed devices. The failure mechanism that is inextricably linked to moisture is corrosion. Along with moisture, a path to the corrosion site, some contaminant (ion), and an electrical potential difference* must all be present for corrosion to proceed.[3]

If all these ingredients are present, corrosion can occur in a variety of ways and places. A broad separation in terms of 'internal' and 'external' may prove useful.[3] Internal corrosion refers to the corrosion of materials *inside* the package. Corrosion of this sort most often occurs at the bond pad or an active circuitry on the die. In both of these cases, it is by moisture penetrating the passivation layer that corrosion takes place.[4] Cathodic corrosion of aluminium results from penetration of the passivation layer by phosphoric acid. Phosphoric acid forms when phosphorus, which is present in phosphosilicate glass, reacts with moisture. Anodic corrosion of aluminium results when chlorine combines with moisture and penetrates the passivation layer. Sources of chlorine include the oxide stripper used in lead cleaning, and handling. In the presence of moisture, other ionic contaminants that penetrate passivation defects can discharge a circuit node, although this is not a permanent failure.

Moisture paths to the *die* are provided by cracks in the plastic package, or via diffusion of water through the plastic package itself: see Figure 1. Moisture paths to the *active circuitry* are provided

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*This potential difference can be due to an applied bias, an electrochemical potential difference, etc.
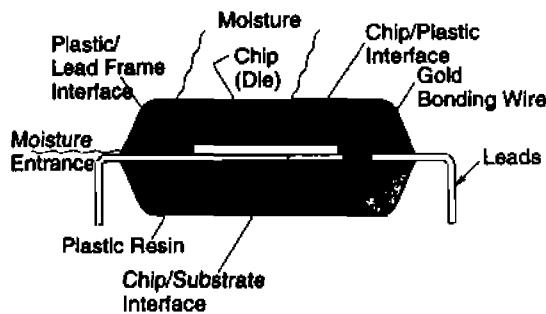
Figure 1. Cross-section of plastic package showing some possible moisture entrance paths

by pinholes in the passivation layer, cracks in the passivation layer resulting from thermomechanical stressing of the package, as well as breaks in the passivation layers because of poor coverage at steps: see Figure 2.

'External' corrosion refers to the corrosion of materials outside the cured moulding compound. External corrosion still requires the same four ingredients: a path to the corrosion site, moisture, contaminant and bias. The mechanisms, however, are more typically lead corrosion (anodic) and metal migration.

Detailed assessment of the likelihood of each failure mechanism, and that of all associated failure modes, is the standard approach to electronic device reliability assessment. So some way of assessing the risk associated with using plastic packaged devices, based on the increased likelihood of these devices' failure because of moisture-related failure mechanisms, is needed. Traditionally, the accelerated life model[5, 6] is used. Use of the accelerated life model is appropriate if a single failure mechanism is the dominant cause of failure over the range of stresses being considered, and if that mechanism may be represented by a single autonomous kinetic equation.[7] A chemical reaction, such as corrosion, is just this sort of process.

It may be, though, that no one reaction dominates. There is no standardized, widely accepted methodology for considering several failure mechanisms that are operating simultaneously.[8, 9] Recent
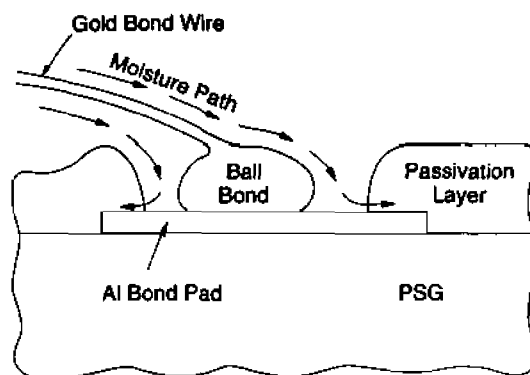
work, however, suggests that the accelerated life model is often reasonable to use, to describe how hostile environments for electronic components increase the risk of failure.[8, 9]

REVIEW OF EXPERIMENTAL RESULTS

Over the years, many investigators have contributed to our understanding of the effect of humidity on the reliability of plastic packaged electronic devices.[2, 10–33] The focus here is on understanding how models of failure may be used to estimate the reliability of devices being tested, or on predicting the reliability of electronic devices that are to be used in electronic systems. Thus, only some of the work need be highlighted. We note that moisture-mediated corrosion is the mechanism of primary concern. We are interested in quantitatively assessing the risk associated with the presence of moisture. Among the experimental work done in this area, two works stand out as particularly important. First, Lawson[2] presented evidence that the rate limiting step (to the occurrence of failure) is *not* related to the diffusion of water through the package material, but is the corrosion reaction itself. Although diffusion could also be modelled, to be able to ignore diffusion in modelling relevant (corrosion) failure mechanisms simplifies the effort.

Another important experimental development may be found in the work of Gunn, Camenga and Malik.[10, 11] They found that the median time to failure, t_{50}, does *not* correlate well with vapour pressure. Gunn, Camenga and Malik found that t_{50} does correlate well with relative humidity. That is, the measure of atmospheric moisture content close to operating electronic devices, that appears to be an *independent variable* at least regarding the degradation reaction leading to failure, is more likely to be relative humidity, rather than the more traditional thermodynamical variable, partial (or vapour) pressure.

REVIEW OF THEORETICAL RESULTS

The two suggestive experimental findings discussed above may be better understood by considering the BET equation.[34] The BET equation[35] was developed by Brunauer, Emmett and Teller[34] as an extension of the original work of Langmuir[36] on adsorption, to consider more than one layer of adsorbate: see Figure 3. The BET equation is given by[34, 35]

Figure 2. Arrows show how moisture may penetrate under the passivation layer (not to scale)
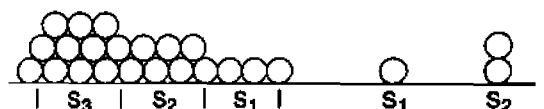

Figure 3. The Brunauer–Emmett–Teller model of multilayer adsorption. The S_i indicate that there are i layers of adsorbate in that part of the surface

$$\Theta = A\frac{x}{(1-x)(1+bx)} \qquad (1)$$

where Θ is the surface coverage, or ratio of adsorbed particles to the number of adsorption sites on the surface. The ratio of partial vapour pressure, p, to saturated vapour pressure, p^0 is given by x. The equation relates surface coverage, a measure of surface concentration, to the ambient vapour pressure of the adsorbed substance. Note that this measure of surface coverage may be greater than one, as *multiple* adsorption layers are considered, unlike the original work of Langmuir. For water, x is the relative humidity, RH.

The constant b is given by

$$b = 1-A = 1-e^{(Q_1-Q_v)/k_BT} \qquad (2)$$

where Q_1 is the heat of condensation of the first monolayer and Q_v is the heat of condensation of the liquid adsorbate. Now we see that according to (1), the surface coverage depends on temperature through A and b, regardless of whether we use p_w, the partial vapour pressure of water, or RH, the relative humidity, as the variable that characterizes moisture content in the atmosphere near a plastic packaged electronic device.

Recall that the experimental findings that we are seeking to take account of are that (a) diffusion through plastic packages is fast compared to corrosive chemical reactions, and (b) relative humidity is the appropriate measure of moisture content, because its effect on the progress of corrosion reactions appears to be independent of temperature.

As the heats of condensation, Q_1 and Q_v, are not expected to be equal in general, we appear to be unable to make further progress towards establishing relative humidity as an independent thermodynamic variable. However, for our purposes, unlike those in the study of surface coverage due to molecular adsorption, it is not the first monolayer that needs to be differentiated from all others. There is little surface current characteristic of solvated ionic movement under the influence of a field without at least several monolayers:[37-39] see Figure 4. So we should be differentiating between some monolayer greater than the first, say the ninth or
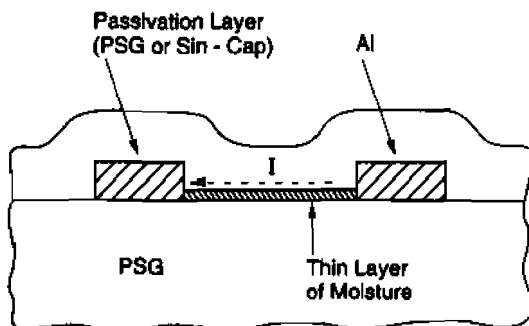
tenth,[37, 38] and all higher number monolayers. Other factors, such as the thermodynamic state of the adsorbed molecules and the nature of the substrate, also affect how many monolayers are needed before surface conduction takes place.[37, 38] The combinatoric arguments underlying the Langmuir work, as well as the BET equation, still apply. In summary, we use the BET equation to describe adsorption on some number of complete monolayers, for example eight, rather than on a solid surface. The heat of condensation associated with the first *new* monolayer, now the ninth, should then be approximately equal to the heat of condensation of all subsequent monolayers. With equal heats of condensation, $A = 1$, $b = 0$, and the BET equation, for adsorption of water vapour, simplifies to

$$\Theta = \frac{RH}{1-RH} \qquad (3)$$

The surface concentration of water now depends on a single variable, RH. If however, partial vapour pressure of water is used as the measure of moisture content in the surrounding atmosphere, then the expression for surface coverage, or surface concentration, *still* depends on temperature as well as vapour pressure, since the saturated vapour pressure of water depends on temperature. This derivative form of the BET equation, (3), provides a relationship between surface concentration of moisture and a variable that is independent of temperature. Now Gunn's result that relative humidity is the quantitative measure of the presence of moisture that correlates with failure times, not vapour pressure, becomes more understandable. If the concentration of moisture on the surface of a die should be expressible in terms of a single variable, and one that is independent of temperature, then there is reason to believe that variable should be relative humidity.

Note that (3), like the BET equation, (1), displays a singularity as RH→1. Experimentally, the surface coverage Θ, may indeed display a rapid increase as RH→1. Such behaviour is characteristic of Type II and Type III adsorption isotherms.[35] And a Type II isotherm is very common in the case of physical adsorption. It is attributed to multilayer adsorption:[35] see Figure 5.

In terms of temperature and relative humidity, various acceleration factor models have been proposed.[40-45] These have been reviewed by Charles,[46] who compared the models that relate t_{50} obtained during the standard 1000 hour test at 85°C/85 per cent RH, to t_{50} at use conditions. Charles also reviewed the comparisons other workers have performed in their reviews of the reliability of plastic packaged electronic devices. Neither the review of Charles, nor those of others before him, offer conclusive statistical findings. That is, by fitting data to the different functional forms, no particular model has been shown to be clearly superior to the others.

Figure 4. Corrosion (ionic) current between biased metal lines in the presence of moisture
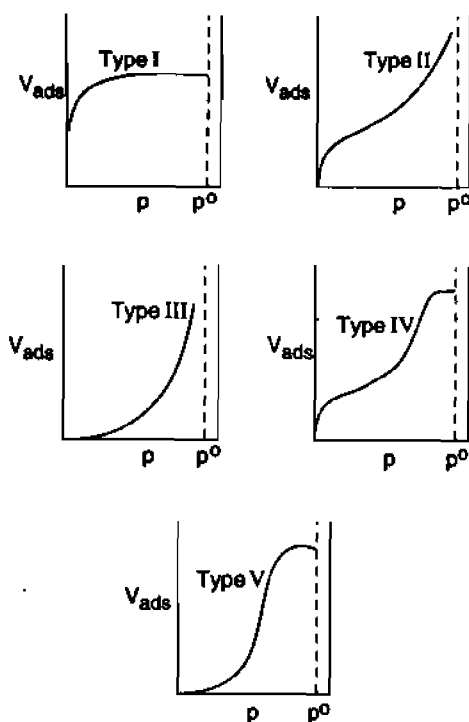
Figure 5. Brunauer's five types of adsorption isotherms

However, physical concepts may be used as guide to choose among candidate models. Many of those models referred to as Eyring models[14, 47-51] are not due to Eyring, but are convenient functional forms for fitting data.[52] As discussed elsewhere,[53] Eyring provided a refinement to the temperature dependence of the Arrhenius model.[53-55] That is, the Arrhenius form for a rate constant, which is used in an acceleration factor, would, according to Eyring, have a function of temperature, T, as a multiplier, where T is the temperature in kelvin. The simplest form for this function is a power law, T^n, where the power n depends on the underlying molecular dynamics associated with the reaction leading to failure.[6, 54, 55] Various other functional forms (which are taken to multiply the rate constant in the underlying degradation reaction leading to failure) that have been associated with Eyring include e^{aRH}, $e^{b/RH}$ and $e^{RH(c+d/T)}$ where a, b, c and d are constants.

The chemistry associated with corrosion of metal on an electronic device is the natural starting point if one is in search of a physically based acceleration factor model. Consider the generic reaction,

$$Al + H_2O + M^{\pm} \rightarrow Al^{+++} + H_2O + M^{\pm} \quad (4)$$

where H_2O represents water in whatever form (hydronium ion, hydroxyl ion, etc.) is appropriate to the particular reaction, and $M^{\pm}$ represents the ionic contaminant, which often goes unconsumed by

the corrosion reaction.* If the rate equation for the overall reaction, (4), may be written as a single equation, then it should be possible to develop an acceleration factor model.[7] For example, consider

$$\frac{d[Al]}{dt} = k[H_2O]^m[Al]^n \quad (5)$$

where $[H_2O]$ represents the surface activity,[56] similar to the surface concentration, of whatever form of water is involved in the reaction.† If the surface concentration of water can be considered to be constant, or even in 'steady state', then the 'effective rate constant' for the reaction may be taken to be given by $k' = k[H_2O]^m$ rather than k, the rate constant. In this case, the associated thermal acceleration factor is given by[6, 7]

$$A(T_1, T_2) = \frac{k_2([H_2O]_2)^m}{k_1([H_2O]_1)^m} \quad (6)$$

where the subscripts 1 and 2 denote rate constants and concentrations at the temperatures T_1 and T_2, respectively. With the BET equation, this expression for the thermal acceleration factor, which now depends parametrically on surface concentration of moisture, may be re-expressed in terms of relative humidity, RH. As the relative humidity is independent of temperature, we may consider the relative humidity as an independent variable, and not just a parameter. The acceleration factor may now be written

$$A(T_1, RH_1, T_2, RH_2) = \left(\frac{RH_2}{1-RH_2} \frac{1-RH_1}{RH_1}\right)^m \frac{k_2}{k_1} \quad (7)$$

where the subscripts 1 and 2 now refer to different sets of environmental conditions, that is different temperatures and relative humidities.

This form bears some resemblance to the power law forms expounded by Peck and Zierdt[42] and Peck.[45] If the surface concentration of water in (5) were taken to be given by the relative humidity, i.e.

$$\Theta = [H_2O] = RH \quad (8)$$

rather than the derivative form of the BET equation given by (3), then Peck's form for the acceleration factor would be obtained. But it is for RH→0 that Θ→RH, which is not a limit of RH that is of practical interest.

Note that as RH→1, (3) and (7) are singular, and so are not valid if the RH is sufficiently close to 1. On the other hand, for relative humidities that are practically achievable in a 1 atmosphere test

*For example in the electrolytic metal attack[1, 30, 31] (EMA, a type of corrosion reaction) of chloride, Cl⁻, with aluminium, the ionic contaminant, chloride, is released as an end product of the reaction, allowing more corrosion if water is present.
†Similarly for [Al].

chamber, typically no more than 0·95 RH, (3) and (7) are of course finite.

To go beyond Arrhenius, the dependence of the acceleration factor on other variables such as voltage may be included by considering the dependence of the activation energy on such variables.[54] This should be distinguished from other variable activation energy models[47, 48] which contain a term proportional to the non-thermal stress variable, *which is not divided by temperature*, in the exponential. Such models lack the theoretical basis[52] of a thermodynamically consistent model which considers the dependence of the activation energy on non-thermal stress.[54]

CONCLUSIONS

The failure mechanisms associated with the effects of humidity on plastic packaged devices have been briefly reviewed. The physical basis for acceleration factor models that are appropriate to include the effects of humidity has been discussed, and an alternative acceleration factor following from these considerations has been suggested. In future work, the utility of this form, which is motivated by theoretical considerations, will be examined.

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