

Chapter 10

Impact of Humidity and Contamination on Surface Insulation Resistance and Electrochemical Migration

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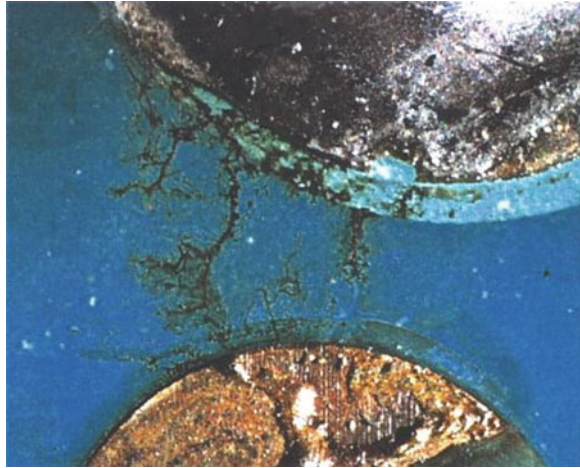
10.1 Introduction

Adequate evaluation of the impact of humidity and contamination on the reliability of electronic circuitry must be based on acceleration of the crucial failure mechanisms that will occur in field conditions. When electronic products are used in humid environments, water will be adsorbed on most surfaces. The amount of water adsorbed will depend on the temperature and the relative humidity but also on the properties of the surfaces. More water will be adsorbed on hydrophilic surfaces compared to hydrophobic surfaces. When polymeric materials are used, these materials may also absorb water. The adsorbed and absorbed water will affect the surface insulation resistance (SIR) on the circuitries. On clean surfaces, the decrease in SIR will normally be too small to affect the functionality of the product, but if ionic contamination is present, the drop in SIR may be large enough to cause failures.

Humidity and contaminants do not only affect SIR. They may also cause electrochemical reactions resulting in oxidation of anodic conductors. Metal ions formed by the oxidation reaction can under certain conditions migrate towards cathodic conductors and there be reduced back to metal. The precipitated metal will form tree-like metal filaments called dendrites. These will grow towards the anodic conductor where the metal ions come from and, with time, may cause a short circuit when they reach the anodic conductor (Fig. 10.1). This failure mechanism is called electrochemical migration (ECM). There is also another failure mechanism closely related to ECM resulting in the formation of conductive anodic filaments (CAFs). The main difference between these two failure mechanisms is that formation of CAFs occurs within a laminate, whereas formation of

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Fig. 10.1 Dendrites formed on an assembly exposed to condensation. The dendrite to the right has caused a short circuit and has been partly blown away by the resulting electric discharge



dendrites normally occurs on the surface of a laminate or a component. However, only failures due to degradation of SIR and formation of ECM will be covered here.

10.2 Definition of Terms

Surface insulation resistance testing has long been used to evaluate the impact of contaminants on current leakage and dendrite formation. However, it may be difficult to interpret the results from such testing since misconceptions and poor understanding of the objectives of SIR testing are common [1]. The difficulties with using SIR testing as a tool for reliability evaluations of assemblies are caused by several factors. The most important are as follows:

- Lack of definitions of expressions used or inconsistent use of defined expressions
- Insufficient knowledge of the failure mechanism
- Poor understanding of the objective with SIR testing
- Difficulties in testing functional assemblies. Specially designed test patterns are required for adequate testing

Surface insulation resistance is defined in IPC-9201 [2] as “a property of the material and electrode system. It represents the electrical resistance between two electrical conductors separated by some dielectric material(s). This property is loosely based on the concept of sheet resistance, but also contains element of bulk conductivity, leakage through electrolytic contaminants, multiple dielectric and metallisation materials and air”. That is, SIR is defined as a materials system property.

However, the main purpose of almost all SIR test methods used today is not primarily to measure SIR. Instead, the objective is to evaluate the long-term reliability of materials systems in humid environments [2]. One of several failure mechanisms that may affect the long-term reliability is electrochemical migration. It is defined in IPC-TR-476 [3] as “the growth of conductive metal filaments on a printed board under the influence of a DC voltage bias. This may occur at an external surface, an internal interface, or through the bulk material of a composite. Growth is by electro-deposition from a solution containing metal ions which are dissolved from the anode, transported by the electric field and redeposited at the cathode. We are thus excluding phenomena such as field induced metal transport in semiconductors and diffusion of the products arising from metallic corrosion”.

Other failure mechanisms in humid environments that may affect the long-term reliability are degradation of solder masks and conformal coatings, degradation in dielectric strength and corrosion [2]. Most of these failure mechanisms are not or only indirectly related to SIR [4]. Tests to evaluate the impact of humidity are often called temperature–humidity (TH) tests or, if a bias is applied during the tests, temperature–humidity-bias (THB) tests. Many of these tests do not include SIR measurements.

10.3 Description of Failure Mechanisms

10.3.1 Effect of Humidity and Contaminants on Surface Insulation Resistance

Between two conductors of different potential separated by a dielectric material, a current leakage will occur. If the conductors are embedded in the dielectric material, the current leakage will depend on the resistivity of the bulk material. Besides the properties of the dielectric material, the resistivity will also be affected by the amount of absorbed humidity and contaminants present.

When conductors are located on the surface of a dielectric material, the current leakage is determined by the integrated effect of both surface and bulk resistivity. Some current leakage may also occur through the air. Since measurement of the resistance between two conductors on the surface of a dielectric material inevitably will include both bulk and surface resistance, the measured resistance is usually denoted by surface insulation resistance [5, 6]. A special case occurs when the conductors are located between two materials, for example conductors in an inner layer or conductors under a solder mask. The current leakage will then occur through the two bulk materials but also in the interface between the two materials. If contaminants are present in the interface, a large fraction of the current leakage then may take place there.

Dielectric materials that have been properly qualified for production of PCB assemblies have high surface and bulk resistivity. Low surface and/or bulk

resistivity is almost always caused by either improper processing (not fully cured or properly mixed) or contaminants. Furthermore, it is normally the result of ionic conduction caused by non-reacted constituents, by-products and/or ionic contaminants. Since migration of ions is involved in the current leakage, the presence of water is normally a prerequisite for ions to take part in the process. Without water, ions will not be formed. Therefore, ionic contamination has a negligible effect on the resistivity in dry conditions [7].

In humid conditions, the bulk resistivity is normally much higher than the surface resistivity [6]. The reason for this behaviour is that a film of adsorbed water is formed on the surface. On α -alumina substrates, roughly one monolayer of water is adsorbed at 35% RH and more than 5 layers of water molecules at relative humidities higher than 70% [8]. Since the surface of the alumina substrate is hydrophobic, thicker water films can be expected to be adsorbed on hydrophilic organic substrates, but it is more difficult to determine the thickness of adsorbed water films on organic substrates such as epoxy- and polyimide-glass laminates since these materials also absorb water.

Due to the intrinsic ionisation of water into hydrogen and hydroxide ions, an adsorbed water film has always some conductive properties. This may be further enhanced by adsorption of some gases from the atmosphere that form ionic compounds with water, for example carbon dioxide. Nevertheless, the impact of a pure water film on the surface resistivity does not normally pose a problem. The conductivity of an adsorbed water film is much less than for bulk water [8]. A water film five layers of molecules thick has a conductivity approximately two orders of magnitude lower than that of bulk water, and a water film of 20 layers has a conductivity which is still one order of magnitude lower than bulk water. The reduced conductivity is due to a strong interaction between the adsorbed water molecules and the substrates, which affects the properties of the water film. Probably, it is also affected by a non-uniform distribution of the water on the surface.

Hence, SIR is to a very large extent affected by the relative humidity but also by the temperature. An increase in the relative humidity by about 20–30% or an increase in the temperature by 20–30°C have been found to decrease SIR by about one decade on fairly clean boards [6, 9–11].

However, it is the function of the water film as a medium for ionisation of ionic compounds that renders adsorbed water films hazardous. A large impact on SIR will be observed if hygroscopic contaminants are present. At or above a critical relative humidity, many salts absorb water forming a saturated solution of the salt. Thereby, the thickness and electrical conductivity of the adsorbed water film is increased tremendously. In Table 10.1, the critical relative humidities at which this happens are given for a number of halide-containing inorganic compounds.

As shown in Table 10.1, the critical relative humidities vary considerably for the presented compounds. Furthermore, the data for calcium chloride and potassium bromide show that the critical relative humidity is temperature dependent, the compounds become more hygroscopic at higher temperatures.

Table 10.1 Critical relative humidities for a number of inorganic compounds at which saturated solutions are formed [12, 13]

Compound	Temperature (°C)	Relative humidity (RH) (%)
LiCl·H ₂ O	20	15
KF	100	22.9
NaBr	100	22.9
CaCl ₂ ·6H ₂ O	24.5	31
CaCl ₂ ·6H ₂ O	5	39.8
KBr	100	69.2
NaCl	10–40	75
KCl	5–25	84
KBr	20	84
NaF	100	96.6

Anderson et al. [14] have shown that the resistivity of a surface contaminated with a hygroscopic compound decreases dramatically when the relative humidity is increased to values above the critical relative humidity for the hygroscopic compound. The resistivity is then rather little affected by a further increase in relative humidity. For an assembled PCB, the surface would be contaminated with a mixture of contaminants from various process steps having varying critical relative humidities. Therefore, the surface resistivity for an ordinary production assembly can be expected to decrease more or less gradually with increasing relative humidity.

Not only ionic compounds may have hygroscopic properties but also polyglycols and many other types of organic non-ionic surfactants common in some types of fluxes and fusing oils are very hygroscopic even at relative humidities down to almost 0% [15]. When present alone, they contribute to a decrease in the surface resistivity mainly by increasing the thickness of the adsorbed water film. Since they do not contribute to ionic conduction, the decrease in surface resistivity is rather small. What makes them hazardous is the fact that they promote a dissolving medium for ionic contaminants with low hygroscopicity that would otherwise be rather harmless except at very high relative humidities. Thereby, strong synergistic effects may be observed when hygroscopic non-ionic compounds are mixed with ionic compounds of low hygroscopicity. For example, as shown in Table 10.2, a mixture of polyethylene glycol and adipic acid has the same impact on SIR as sodium chloride [16]. The figures in Table 10.2 also show that ionic compounds have negligible impact on SIR at relative humidities below the critical relative humidities for the compounds. The reason why NaBr and KCl do not have an impact on the surface conductivity despite a critical RH below that at which the measurements were performed may be due to that surface dispersed chemicals have lower critical RH than the bulk salts [16].

Fortunately, not all contaminants are hazardous. Some are even beneficial. Rosin, a common base in many fluxes is hydrophobic, i.e., water repellent [15]. Therefore, rosin residues decrease the amount of water adsorbed on the surface and thereby improve the surface resistivity. Rosin residues may also encapsulate

Table 10.2 Surface conductivity measured at 35°C and 90% RH for copper comb patterns on FR-4 substrate contaminated with various compounds [16]

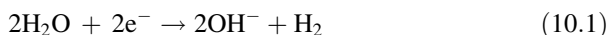
Compound	Added amount ($\mu\text{g}/\text{cm}^2$)	Surface conductivity (ohm^{-1})	Critical RH ^a (%)
NaCl	2.00	1.3×10^{-8}	76
NaF	1.44	4.0×10^{-11}	97
NaBr	3.52	3.8×10^{-11}	84
KCl	2.55	3.1×10^{-11}	84
MgCl ₂	1.63	2.9×10^{-8}	44
CaCl ₂	1.90	9.5×10^{-8}	29
Adipic acid	5.00	2.7×10^{-11}	99.6
PEG 400 ^b	13.70	3.2×10^{-10}	0
Adipic acid + PEG 400	5.00 + 13.70	1.4×10^{-8}	–
None (Reference)	0.00	3.5×10^{-11}	–

^aCalculated values^bPEG 400 = polyethylene glycol with a molecule weight of 400

ionic contamination and thereby immobilise ions. In addition, water that condenses on a hydrophobic surface tends to form isolated droplets as water does on a greasy surface. Thus, even if condensation occurs, rosin residues improve the situation.

10.3.2 *Effect of Humidity and Contaminants on Electrochemical Migration*

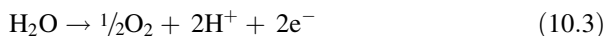
Current leakage due to ionic conduction is usually accompanied by a reduction process at the cathode and an oxidation process at the anode. The cathode reaction may be:



or



Whereas the anode reaction may be:

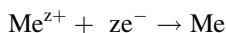


The cathodic reactions give rise to an increase in the pH at the cathode, whereas the anodic reaction brings about a decrease in the pH at the anode. The anode reaction may also involve oxidation of metals forming the anode. All common metals used in conductors can be oxidised including gold, platinum and palladium. However, the three latter can only be oxidised in the presence of contaminants

forming strong complexes with the metal ions, for example chloride, bromide and iodide [17] of which the first two are common ingredients in fluxes. The oxidation of metals at the anode can be written:



Under favourable (or rather unfavourable) conditions, the dissolved metal ions can migrate to the cathode and there be reduced back to metal:



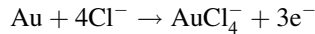
These two latter reactions are the same reactions that occur during electroplating. However, in contrast to electroplating, the metal precipitated in this case is not plated as a metal film on the cathode. Instead, it is plated in tree-like structures called dendrites (see Fig. 10.1). With time, the dendrites may completely bridge the space between the conductors, causing short circuits. Since the dendrites are very thin, short circuits usually burn off part of or the whole dendrite. Thus, failures caused by the formation of dendrites are normally intermittent in nature, and it may be very difficult to track the reason for such failures, especially if the dendrites have been burned off or if they are formed under components where it is difficult to visually observe them.

It has been proposed that the propensity of a metal to form dendrites can be assessed from the standard reduction potential: the lower the standard potential, the larger propensity to form dendrites [18]. Thus, the propensity to form dendrites should decrease in the following order: Ni, Sn, Pb, Cu, Ag and Au. However, the fact that silver has been found to be the metal that easiest form dendrites [3], indicates that it is not only the standard reduction potential that determines the propensity to form dendrites. If dendrites to form, the metal ions produced at the anode must be able to migrate all the way to the cathode without being precipitated as insoluble compounds. As already indicated, acidic conditions can be expected to prevail at the anode and alkaline at the cathode. However, the actual pH of the surface will also depend on contaminants present on the surface. Some common contaminants are alkaline, for example sodium and potassium carbonate from alkaline solder mask developers or residues from alkaline cleaning solutions. Examples of acidic residues are weak organic acids, such as adipic acid, forming a part of many no-clean fluxes.

Rather few, if any, of the metal ions causing growth of dendrites are soluble through the entire pH range that may prevail between the conductors, especially at neutral and high pH. For example, copper dendrites require a pH of less than 5 if they shall be able to form [19]. Silver(I) ions are among those metal ions that are soluble at a rather high pH [20] which is likely one of the reasons why silver has been found to be the metal that easiest form dendrites. When tin is oxidised, tin(II) ions are first formed which may be further oxidised to tin(IV). Tin(II) and especially tin(IV) require very low pH if they shall not be precipitated as hydroxides in water solutions. Lead(II), which is formed when lead is oxidised, is less soluble than silver(I) but more soluble than tin(II) and tin(IV). Thus, lead can expected to

be more prone to form dendrites than tin under right conditions. In addition, for an assembly exposed to field conditions, exposure to high humidity levels will usually be followed by dry-up periods. Soluble metal salts may then be converted to more or less insoluble compounds, which will delay the growth of dendrites.

As already mentioned, gold can only be oxidised in the presence of certain anions, notably chloride, bromide and iodide. These are anions that form very strong soluble complexes with gold ions. In the presence of chloride ions, the anode reaction can be written:



The strong complexes formed with chloride also make gold ions soluble in solutions with rather high pH, thus facilitating the migration of gold ions towards the cathode and thereby the formation of gold dendrites. Chloride and bromide ions form strong complexes also with cations of silver, copper, tin and lead. In fact, that is the reason why they are added to fluxes. Their strong tendency to form complexes with the metals commonly used as surface finishes facilitates the breaking of the oxides on these surfaces during the soldering process. Consequently, many of the substances added to fluxes in order to facilitate soldering can be expected to form strong complexes with metals common in surface finishes of printed boards although not necessarily as strong as those formed with chloride and bromide. The presence of complex-forming compounds is highly favourable for the formation of dendrites and is likely a prerequisite for dendrites to form in most cases.

An interesting fact is that most complexes formed with chloride and bromide ions have a negative charge. For example, the complexes that may form between silver and chloride, AgCl , AgCl_2^- , AgCl_3^{2-} and AgCl_4^{3-} , are either neutral or negatively charged. The concentration of each species depends on the concentration of chloride ions in relation to silver ions. The larger the surplus of chloride ions, the higher the concentration of the species with three and four chloride ligands. Thus, in the presence of chloride and bromide ions, migration of silver ions from the anode to the cathode will not be driven by the potential difference since it will work in the opposite direction. Migration would be driven by difference in concentration. Formation of highly negatively charged complexes may also explain the finding by Bumiller et al. that as chloride contamination increases, the failure mechanism shifts from ECM to uniform corrosion of the anodic conductor [21]. Hence, it is possible that dendrites would form faster if power-off periods were included in the test, under condition that the humidity level is preserved.

10.4 Performance of SIR and ECM Measurements

It is far more complicated to measure SIR than it may seem at a first glance. Moreover, as discussed previously, the purpose of most “SIR test methods” is not

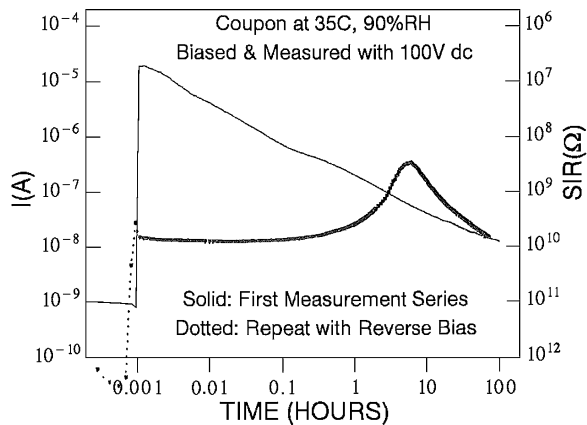
to determine the SIR but to determine the risk for electrochemical migration. Therefore, the complexity and purpose of SIR measurements and the connection to ECM testing will first be discussed before test methods for SIR and ECM tests are reviewed.

10.4.1 SIR Measurements

SIR is determined using Ohm's law $R = U/I$. In humid conditions, most of the current on contaminated boards is generated by migration of ions. This will cause a depletion of ions in the area between the biased surfaces, which will result in a decrease in the current, i.e., an increase in SIR. Thus, measuring of SIR will affect the measured value. As shown by Chan [22], the increase in SIR on a contaminated board is fast at the beginning and then getting slower and slower. When a board was contaminated with 10 mg/in^2 (1.56 mg/cm^2) table salt, the initial SIR was 5.3×10^6 ohms at 30°C and $90\% \text{ RH}$ compared to about 1×10^{10} ohms for a clean board. When a bias of 100 V DC was applied to the contaminated board, SIR increased to 3.7×10^7 ohms after 60 s , 1×10^9 ohms after a few hours and 8×10^9 ohms after 100 h (Fig. 10.2). The clean test board showed almost no drift in SIR values. Thus, the SIR on the contaminated board approached the value of the clean board after 100 h of testing.

Obviously, in order to get reproducible data, one must define a stabilisation (electrification) time after the voltage has been applied before a measurement is taken. Many standards prescribe a stabilisation time of 60 s , but that may be a little too short since the SIR may still drift rather fast after 1 min [10, 22]. On the other hand, waiting too long will cause a too large drift in SIR. Furthermore, a measurement of SIR will be affected by previously performed measurements. This influence will be larger the longer the stabilisation time is. Another implication of the ionic contribution to current leakage is that the measured SIR and the optimal

Fig. 10.2 Current and SIR for coupon contaminated with $10 \text{ } \mu\text{g/in}^2$ table salt [22] (© 1996 IEEE)



stabilisation time will depend on the applied voltage but also on the geometry of the test pattern.

The test patterns most frequently used for SIR and ECM testing are Y and interdigitated comb patterns of various designs, of which some are shown in Fig. 10.3.

In order to get test patterns that are more representative for the circuitry on PCBs, interdigitated solder lands have also been used. Three examples of such patterns are shown in Fig. 10.4. The two first types of test patterns have also comb patterns beneath the component bodies. In order to minimise current leakage between the test patterns for the interdigitated solder lands and the comb patterns, the connectors connecting the solder lands and the comb patterns should be coated with a solder mask.

The distance between the conductors and their number and length will all affect the SIR of a test pattern. Therefore, it is difficult to compare SIR values measured for patterns of different design. Ideally, this can be handled using the ohms/square concept [6]. If SIR is assumed to obey Ohm's law, the SIR for a square will be independent of the size of the square. By calculating the total number of squares in a test pattern (dark grey area in Fig. 10.5) and then dividing the measured SIR with the total number of squares, SIR can be expressed as ohms/square. If SIR had obeyed Ohm's law, this value would have been independent of test pattern geometry. However, in reality, it has been found that SIR does not obey Ohm's

Fig. 10.3 Examples of comb patterns and a Y-pattern from Test Board IPC-B-25A used for SIR and electrochemical migration testing

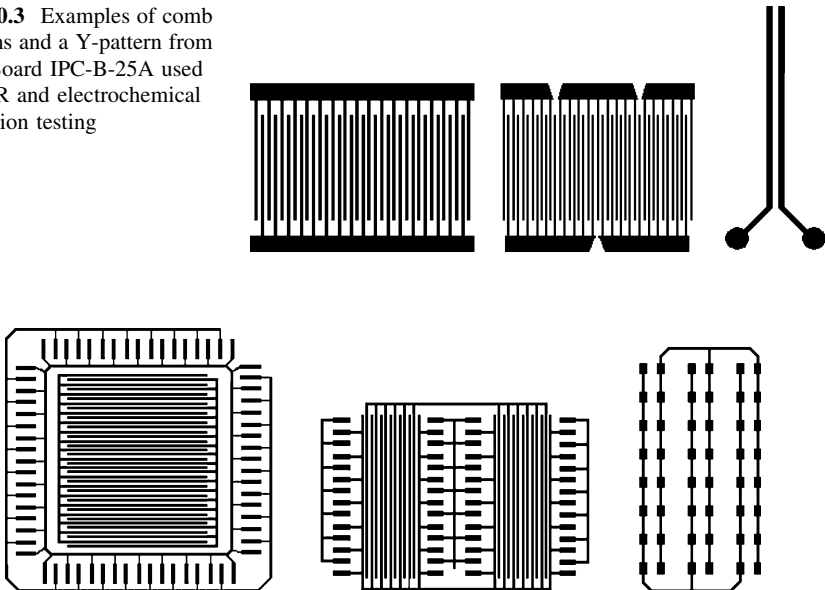
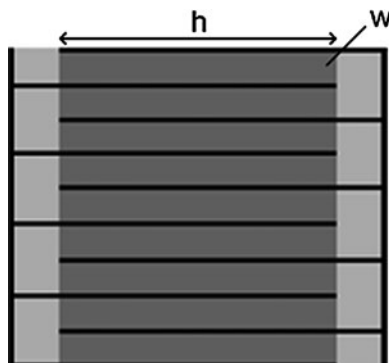


Fig. 10.4 Test patterns for measuring SIR between solder lands to an LCCC68 or PLCC68 component, two SO28 components and 0805 chip capacitors. Comb patterns are located beneath the IC components

Fig. 10.5 The number of squares for the area of interlap in a comb pattern (*dark grey*) is calculated by dividing the length (h) of the conductors in the interlap area with the conductor spacing (w) and then multiplying by the number of conductors (n) minus one, i.e., $h(n-1)/w$



law due to the ionic conduction, so this concept should be used with caution [2, 23]. Furthermore, the current leakage will not be restricted to the area coloured dark grey in Fig. 10.5. Some current leakage will also occur in the light grey area. This will not have any significant impact on the calculated ohms per square values as long as the length of the conductors is much larger than the insulation distance between the conductors, as in comb patterns, but it will have a large impact on the values for interdigitated solder lands.

10.4.2 Purpose of SIR Measurements and Connection to ECM Testing

In many SIR test methods, a bias is applied to the test patterns during part of or for the whole test period, which may have a duration of up to 56 days. Although SIR is measured during these tests, the purpose of such extended tests is not to determine the SIR. Instead, the objective is to assess to the long-term effect of exposure to humidity and then especially the risk for electrochemical migration. Thus, a more appropriate name of such a test is electrochemical migration test.

The fact that SIR is measured during these tests may give the impression that the risk for electrochemical migration can be measured and determined from the measured SIR values. That is not usually the case. Although electrochemical migration causes migration of metal ions, it is not possible to separate electric current due to migrating metal ions from current due to other migrating ions. Thus, it is not possible to determine from a measured SIR value if, and to what extent, migration of metal ions have occurred. Moreover, the formation of a dendrite does normally not have any impact on SIR except for a few seconds when a short circuit is formed [3]. Due to the very small cross-sectional area, a part of the dendrite is burned off almost instantly when the short circuit occurs. Since SIR in most tests is measured once a day, or even less frequently, and each measurement takes less than a second, it is very unlikely that a very short drop in SIR would be detected.

Some modern instruments are designed to automatically measure SIR at a high frequency [24]. By using these instruments, the chance to detect an intermittent short circuit increases, but there is still a risk for missing failures that will occur. This could be mastered by using an event detector similar to the type used for detecting intermittent open circuits in solder joints, but in this case designed to detect intermittent short circuits. The time elapsed before a short circuit occurs would be a good measure of the propensity for dendrite formation.

As long as event detectors are not used to detect short circuits, dendrites have to be detected using some other method. Today, this is done by visual examination of the test boards using an optical microscope after the test has been run. If test patterns are located beneath components, it may be necessary to remove the components before the inspection. Using visual inspection, only the number, size and location of dendrites can be evaluated. It is not possible to determine when they were formed during the test. Furthermore, current-limiting resistors must be connected in series with each test pattern during the test in order to prevent that dendrites are completely burned off when a short circuit is formed.

If electrochemical migration cannot be detected by SIR measurements, then why measure SIR at all during an electrochemical migration test? Although there is no clear correlation between SIR and the inclination for dendrite formation, a high SIR indicates that electrochemical migration is unlikely to occur and a low SIR indicates an increased risk for dendrite formation. However, it is not possible to exclude that dendrites will form if SIR is above a certain value, nor will dendrite formation be inevitable if SIR is below a certain value. A large number of parameters not directly correlated to SIR have a large impact on the inclination for dendrite formation, for example, as previously discussed, the pH of the surface and the presence of substances forming strong complexes with metal ions.

There are also other factors that will affect the results from SIR and ECM tests. Originally, SIR measuring was done with an instrument using 500 V DC as measurement voltage [4]. Several standards still prescribe that a measurement voltage of 100–500 V DC should be used. Today, with much shorter insulation distances and lower voltages, this is a far too high voltage for many applications. Even if the applied polarisation bias generally is lower, a polarisation bias of 50–100 V DC is common. Such a high polarisation bias may induce failure mechanisms that would not occur in field conditions. Not only will the increased electrical field cause an increased migration rate of ions, but it will also increase the rate of the oxidation and reduction reactions at the anode and the cathode, respectively. This will cause concentrations of ionic species that would not be found on a true product. Furthermore, the pH gradient between the conductors would be larger than normal, i.e., the pH would be lower at the anode and higher at the cathode. Thus, the surroundings for migrating metal ions may be quite different from those experienced in field conditions. Therefore, it is advisable to not use polarisation and measurement voltages that differ too much from the voltage to be used for the final product. To be on the safe side, polarisation and measurement voltages not higher than twice the service voltage gradient have been recommended [4].

Due to the continuous increase in SIR caused by depletion of ions in the area between biased conductors during an ECM test, some standards prescribe that measurements of SIR should be taken using a voltage with reversed polarity and a stabilisation time of 60 s. As expected, by reversing the polarity, the SIR will first drop as ions start to migrate in the opposite direction and then increase again after some time when the area between the conductors once more becomes depleted of ions. The drop in SIR may begin immediately but, as shown in Fig. 10.2, it may also take more than 1 h before it occurs and 10 h to reach a minimum [22]. Therefore, using reversed bias when measuring SIR only makes it even more difficult to interpret the results of ECM tests. Since also a change of voltage with retained polarity will cause an unpredictable drift of SIR, measurements should preferably be done using the same voltage and polarity as the polarisation bias and without any interruption of the bias.

However, unbiased periods during the measurement could be used for another reason, but then they should be of some length and not performed directly before measurements are taken. As discussed previously, metal ions are probably in many cases mainly present as negatively charged complexes. Thus, the migration of these to the cathode must be by diffusion against the electrical field. A test consisting of periods with applied bias followed by periods without any bias to allow for “free” diffusion would then perhaps be a more adequate test producing dendrites in a shorter time.

Zou and Hunt have proposed a fast method to predict the propensity for electrochemical migration of solders and PCB finish materials based on Electrochemical Impedance (EI) measurements [25] (see Chap. 4). Using this method, the ionic resistance between two electrodes can be separated from the overall impedance of the system. The former was found to be dependent on the metal corrosion rate and solubility of the metal hydroxide. The propensity for dendrite formation for various materials was shown to have an inverse correlation with ionic resistance.

10.4.3 Test Vehicles

Production of test boards will inevitably cause contamination of the boards from processing solutions. Figure 10.6 shows the change of SIR during an ECM test for printed boards with different surface finishes produced by one printed board manufacturer using ordinary production processes [26].

Initially, the boards with HASL (hot-air solder levelling) finish have about five decades lower SIR than the boards with OSP (organic solderability preservative) and ENIG (electroless nickel/immersion gold) finishes. The much lower SIR values for the HASL finish is due to residues from the flux used in the HASL process. Due to the fact that it is impossible to clean away all flux residues [27, 28], HASL boards will always have rather low SIR. However, the impact of flux residues from different printed board manufactures may vary greatly.

Fig. 10.6 Surface insulation resistance measured during an electrochemical migration test performed at 85°C, 85% RH and 5 V DC polarisation and measurement voltage for comb patterns on printed boards with the following surface finishes: HASL (*filled square*), ENIG (*open square*) and OSP (*filled diamond*)

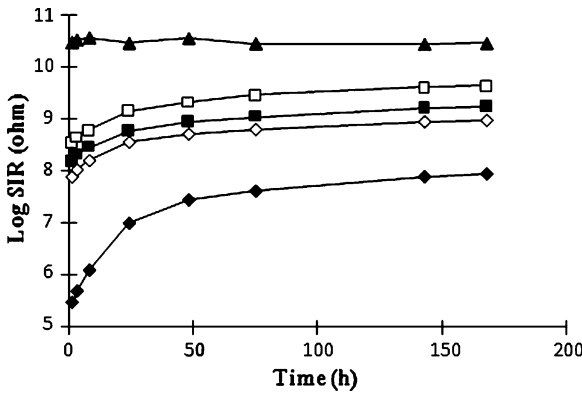
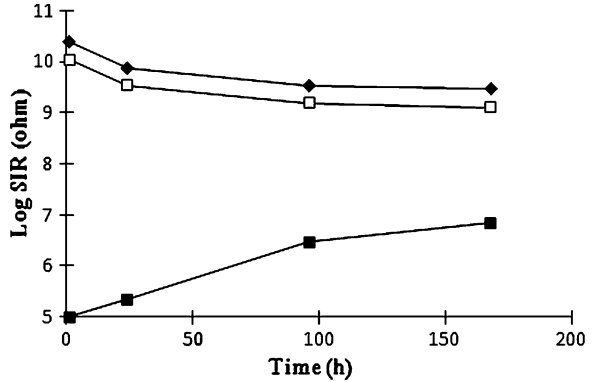


Fig. 10.7 Surface insulation resistance measured during an electrochemical migration test performed at 65°C, 85% RH and 5 V DC polarisation and measurement voltage for comb patterns on printed boards from four printed board manufacturers: A (*filled square*), B (*open square*), C (*filled diamond*) and D (*open diamond*). For reference, results are given for a board from manufacturer A cleaned for 2 h before the test (*filled triangle*)

Figure 10.7 shows the results from SIR measurements of HASL printed circuit boards from four printed board manufacturers [27]. Initially, the SIR values differ three decades between the best and the worst boards. With 2 h of extensive cleaning using ultra-sonic agitation of boards from Manufacturer A, the SIR was improved by about two decades, i.e., to about the same value as OSP and ENIG boards if the SIR is adjusted for the difference in test temperature. However, when a thoroughly cleaned board went through a soldering process without any added flux, the SIR decreased almost back to the original value indicating that absorbed flux residues diffused up to the surface during the heat treatment [27].

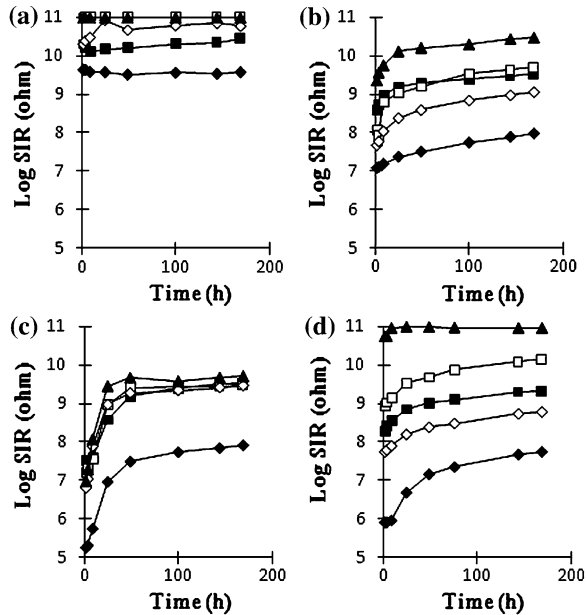
To minimise the effect of contamination, test boards with bare copper patterns, without any solder mask applied and extensively cleaned are often used.

Thereby, the effect of a single material, chemical or process can be evaluated. Passing such a test is mandatory but not sufficient for approval of a material. When various materials and processes are combined, synergistic effects may occur. For example, as shown by Adams et al. [16], polyethylene glycol which is a common ingredient in fluxes used for HASL gives a strong synergistic effect when combined with adipic acid, a common ingredient in many no-clean fluxes used for soldering of assemblies (see Table 10.2).

The cleanliness of a printed board will affect the SIR of an assembled board whether cleaning of the assembly is performed or not. Figure 10.8 shows the results from measuring SIR on assemblies soldered at some assemblers having different types of soldering processes using printed boards from the four manufacturers presented in Fig. 10.7 [27]. Although the absolute measured SIR values varied considerably for the various assemblies, the variation in SIR on the printed boards was reflected in the SIR of the assemblies independent of the type of flux and cleaning process used. It can be noted that rosin residues have a very benign influence on SIR even when cleaning is performed.

Thus, one has to choose between a comparatively clean test board with a copper pattern and no solder mask, and a test board that is more representative for what will be used in true products. In the first case, it will be possible to evaluate the influence on SIR of a single material, chemical or process and to compare with data from other investigations, but it will not be possible to draw reliable conclusions regarding the SIR on the final product. In the second case, the results will

Fig. 10.8 Surface insulation resistance measured between solder joints to wave soldered SO28 components on assemblies manufactured by three different assemblers using their ordinary processes: RA flux and solvent cleaning (a), low-solid, rosin-based flux and no cleaning (b), water soluble flux and cleaning using pure water (c) and non-soldered reference boards (d). The printed boards used were produced by Manufacturers A (filled square), B (open square), C (filled diamond), D (open diamond) and, as reference, boards from manufacturer A cleaned for 2 h before soldering (filled triangle)



show the SIR properties of the final product but they will only be representative for the combination of materials, chemicals and processes used for producing the test boards. Hence, “clean” test boards are mainly used for screening of materials and processes, although it is not desired that material qualification be limited to that. It may lead to approval of materials that later will be found to cause unreliable products. Consequently, test boards used for final verification need to be representative of the materials and processes used in production. That is, final verification can only be done for specific applications. This is reflected in IPC’s standard for printed board assemblies (PBAs): J-STD-001D, Appendix C, Material and Process Compatibility Testing, which specifies that the test vehicle should represent the substrate materials, assembly materials and fabrication processes used in production [29].

However, comb patterns are not appropriate for such evaluations. The locations most contaminated and difficult to clean on a PBA are areas between solder joints and beneath components. Furthermore, due to the shadowing effect of components, flux residues underneath components will not be heated to the same temperature as on the rest of the assembly. Therefore, they may not be deactivated or evaporated as they would have been on a free surface. Hence, to truly represent manufacturing processes, it is necessary to mount components on the test boards. By mounting dummy components without any electrical connections inside (open circuit) on test patterns of the type shown in Fig. 10.4, SIR can be measured between solder joints to soldered components. In fact, a test board can be designed and produced exactly in the same way as production PBAs. The results presented in Fig. 10.8 are from measurements of SIR between solder joints to SO28 components soldered to printed circuit boards.

By placing comb patterns under components, SIR can also be checked at such locations, although it must be pointed out that the comb pattern can have some influence on the efficiency of a cleaning process for components with small stand-offs. Ceramic chip capacitors and resistors usually have a very small stand-off, and it is difficult to clean beneath them, especially if they are glued to the boards using glue dots at the sides of the components. The best way to measure SIR beneath this type of components is to use a test pattern as shown in Fig. 10.4, but then only chip capacitors can be used. After the capacitors have been charged, the SIR can be measured.

10.5 Common Contaminants that may Affect SIR and ECM

Contamination on electronic circuits may originate from manufacturing of printed boards and assemblies, handling, storage, transportation, use, rework and repair. Contamination from all these phases of a product’s life may affect SIR and ECM.

10.5.1 Contamination from Manufacturing of Printed Boards and Assemblies

The most common laminate used for production of printed boards is FR-4, glassweave-reinforced epoxy. When the epoxy resin in the laminate is cured, small amounts of sodium chloride is formed as a by-product [30]. To render some resistance against fire, brominated flame retardants are added to the laminate. The function of the brominated flame retardants is to liberate hydrogen bromide when exposed to fire. However, some decomposition may already occur during soldering processes [31]; the higher the soldering temperature and the longer the exposure to high temperatures, the more hydrogen bromide is liberated. Furthermore, to render solder masks UV-curable, photo-initiators are added which are not included in the polymerisation reaction [30]. Thus, the board materials themselves contain contaminants of which some are ionic. Also, if the epoxy is under cured, flux ingredients may react with flame retardants at the surface liberating bromide ions [31].

The production of PCBs includes many wet chemical treatments which all may leave residues. Examples of chemical processes are desmearing of drilled holes, etching processes, plating of copper and surface finishes and cleaning processes. It is important that thorough cleaning is performed in order to remove as much as possible of process chemicals.

The most contaminating process used for PCB fabrication is application of solder, whether it is applied using hot-air solder levelling (HASL) or hot-oil fusing. This process involves fluxing of the boards followed by heating to 240–280°C during solder application or hot-oil fusing, i.e., at temperatures far above the glass transition temperature (T_g) for FR-4 laminates and around the T_g for polyimide laminates [32]. The polymer resin in the laminate becomes soft at temperatures around and above T_g , and flux ingredients are absorbed into epoxy resins by this treatment [27, 33] and probably also into polyimide resins. Epoxy and polyimide laminates may absorb flux ingredients to some extent even at temperatures as low as 125°C [34].

One group of ingredients that may be absorbed is polyglycols. It has been known for a long time that polyglycol materials are absorbed into the epoxy resin of FR-4 boards and that it is very difficult to remove these residues by cleaning [35, 36]. Inorganic ionic compounds may also be absorbed. High concentrations of chloride and bromide have been found in FR-4 laminates and solder masks [27, 28]. These residues are not possible to remove completely even if very efficient cleaning processes are used. The halides are believed to originate from fluxes used for HASL or fusing. There are indications that halides may diffuse through several layers in multilayer boards [37].

Fluxes used for soldering of assemblies will also leave residues on the surface, and some of the flux ingredients may be absorbed into the resin.

10.5.2 Contamination from Handling, Storage and Transportation

Common contamination sources during handling, storage and transportation are fingerprints and dust from the environment and packaging materials. Fingerprints contain hygroscopic salts of which a large part is sodium chloride. They also contain organic acids that may form strong complexes with copper, silver, tin and lead ions. Thus, fingerprints have large impact on surface resistivity, and they promote the formation of dendrites. The composition of dust varies considerably between different locations. They may have a high content of ionic materials.

10.5.3 Contamination from Use Environments

Assemblies often become contaminated in the field environment. Especially for assemblies that are cooled by forced-air circulation, this contamination may be significant.

The contamination can be divided into two main classes, gaseous and particulate contaminants. Gaseous contamination consists of gases that will cause corrosion of metals. The primary failure mechanism caused by corrosive gases is contact failures in electrical contacts. Corrosion attacks on conductors, solder joints and component leads on assemblies may affect SIR and the formation of dendrites. However, most corrosion products formed, for example oxides and sulphides, are rather insoluble in water and do not contribute to ionic conduction. An exception is corrosion products formed by hydrogen chloride and chlorine, i.e., metal chlorides. Besides being soluble and thereby contributing to ionic conduction, they are also a source of halide ions, which promote electrochemical migration.

For most applications, particulate contamination is a much larger source of ionic contamination than corrosive gases [38]. Particles are usually divided into two size-groups, coarse and fine particles [38, 39]. Coarse particles (>1 mm diameter) originate mainly from mineralogical or biological sources, whereas fine particles (<1 mm diameter) have mainly anthropological origin. Although fine particles are much more abundant than coarse ones, the total mass in outdoor environments is usually about the same for the two size-groups. Ionic components in fine particles are mainly sulphate and ammonium [40]. The content of ionic species in coarse particles shows large variations between various locations. Sulphate, ammonium, calcium, magnesium, sodium and chloride normally are the most prevailing ionic components with large local variations for the three latter.

Most of the coarse particles are usually trapped by filtration systems but only a small portion of the fine particles is removed unless high efficiency filtration is used [38]. The deposition rates of various ions on a free, horizontal zinc surface in a typical electronic equipment room (telephone office) are presented in Table 10.3 [41]. An investigation of an electronic equipment manufacturing environment

Table 10.3 Average annual accumulations of ions on a horizontal zinc surface [41]

Substance	Concentration ($\mu\text{g}/\text{cm}^2$)
Sulphate	0.20–0.35
Chloride	0.23
Nitrate	0.13–0.26
Sodium	0.11–0.15
Potassium	0.08–0.18
Magnesium	0.03–0.05
Calcium	0.63–0.87

showed a concentration of particles about five times higher in the factory environment compared to electronic equipment rooms [42]. Of course, there can be very large local variations, both regarding the amount of airborne particles and their composition. In equipment without forced-air cooling, the deposition of particles will be much less compared to a free surface. On the other hand, if forced-air cooling is used, the deposition rate can be expected to be much higher [43].

As indicated, indoor airborne particles consist mainly of sulphate and ammonium at most locations. The ammonium/sulphate ratio is normally found to be between one and two, i.e., the formula can be written $(\text{NH}_4)_{2-x}\text{H}_x\text{SO}_4$ where x varies between 0 and 1. The critical relative humidity at room temperature for $(\text{NH}_4)_2\text{SO}_4$ and NH_4HSO_4 is approximately 80 and 40%, respectively. These values correspond to the observation that deposits tend to be very hygroscopic above 50–65% relative humidity [39].

Contamination may also occur in the form of liquid droplets containing, for examples, oils and fuels. These are usually not ionic or hygroscopic but they may affect the protective properties of conformal coatings.

10.5.4 Contamination from Rework and Repair

When rework and repair are performed on assemblies, this may cause considerable contamination of the boards due to decomposition of board materials and fluxes used for the work. In addition, it is usually not possible to use the same type of efficient cleaning processes as is used in the assembly line, especially if the work is performed in the field. Therefore, reworked and repaired boards normally have higher levels of contamination than boards that have not been reworked or repaired.

10.6 Surface Insulation Resistance and Electrochemical Migration Test Methods

Test methods for SIR and ECM testing may have one of three purposes:

- Qualification of materials

- Qualification of material combinations and manufacturing processes
- Evaluation of performance in field conditions

10.6.1 Test Methods for Qualification of Materials

For a long time, testing was almost exclusively performed in order to qualify specific materials. Some examples of such tests are as follows:

- IPC-TM-650, Test Method 2.5.27, Surface Insulation Resistance of Raw, Printed Wiring Board Material [44]
- IPC-TM-650, Test Method 2.6.3F, Moisture and Insulation Resistance, Printed Boards [45]
- IPC-TM-650, Test Method 2.6.3.1D, Moisture and Insulation Resistance—Solder Masks [46]
- IPC-TM-650, Test Method 2.6.3.3B, Moisture and Insulation Resistance—Fluxes [47]
- IPC-TM-650, Test Method 2.6.14A, Resistance to Electrochemical Migration, Polymer Solder Mask [48]
- Bellcore TR-NWT-000078, Method 13.1.5, Electrochemical Migration [49]

10.6.2 Test Methods for Qualification of Material Combinations and Manufacturing Processes

Since the test boards used for qualification of materials only have Y or comb patterns and usually bare copper finish, interactions between various materials and contaminants that can be found on an assembly will not be evaluated. Therefore, while passing the tests is mandatory for approval of a material, it is no guarantee for that it will not cause reliability problems when mixed with other materials and contaminants that may be present on an assembly.

For this reason, it is required in IPC's standard for soldered electrical and electronic assemblies [29] that "The materials and processes used to assemble/manufacture electronic assemblies shall be selected such that their use, in combination, produce products acceptable to this standard. When major elements of the proven processes are changed (e.g., flux, solder paste, cleaning media or system, solder alloy or soldering system), validation of the acceptability of the change(s) shall be performed and documented. They can also pertain to a change in bare board supplier, solder resist or metallization". It is up to the user and manufacturer to agree how this should be done but an example of a method for accomplishing it is provided in Appendix C to the standard.

The method in Appendix C is based on SIR testing and visual inspection after finished test. It is specified that "The test vehicle should represent the substrate

materials, assembly materials and fabrication processes used in the production. The test vehicle circuitry must provide for SIR testing similar to the IPC-B-36 circuitry”. The IPC-B-36 circuitry consists of interdigitated solder lands to LCCC68 components as shown in Fig. 10.4. Furthermore, “Components of the type to be soldered in production representative of the “hardest-to-clean” configurations (in term of “shadowing” of the solder connections by component bodies and component-to-substrate spacing) shall be included on the PWA”. Test vehicles for products that will be used in non-condensing service environment shall be tested in accordance with IPC-TM-650, Test Method 2.6.3.3 [47], whereas test vehicles for products that will be used in condensing service environments shall be tested in accordance with IPC-TM-650, Test Method 2.6.3, Class 3 [45]. In the latter case, the test vehicles shall be conformally coated using the same coating material/application processes used in “delivered” hardware. In both cases, it is THB tests. When testing according to Test Method 2.6.3.3, the test vehicles are exposed to 85°C and 85% RH for 168 h. SIR measurements are performed after 24, 96 and 168 h. A bias of 45-50 V DC is applied during the test and measurements are taken using a test voltage of –100 V DC (i.e., reversed polarity).

That is, the purpose of the method in Appendix C to IPC J-STD-001D is to qualify the material combinations and manufacturing processes used for production of a specific product. A similar approach is taken in the IEC standard 61189-5, Test 5E02: Surface insulation resistance, assemblies [50]. The test board to be used for the measurements can be equipped with several types of components (QFP, BGA, SO, surface mount and trough-hole mount connectors and surface mount capacitors). These have circuitry similar to those shown in Fig. 10.4. The test conditions for the IPC and IEC test methods are compared in Table 10.4.

Table 10.4 Test conditions specified for IPC test methods 2.6.3 and 2.6.3.3 and IEC test 5E02

	IPC Test 2.6.3.3	IPC Test 2.6.3, Class 3	IEC Test 5E02
Temperature/ RH	85°C/85% RH	20 cycles 25–65°C/85–93% RH	40°C/93% RH ^a or 85°C/85% RH
Duration	168 h	160 h	Minimum 168 h
Bias	45–50 V DC	100 V DC	5, 50 or 100 V DC ^b
Test voltage	–100 V DC	Optional ^c but with the same polarity as the bias voltage	5 or 100 V DC ^b
Measurement frequency	After 24, 96 and 168 h	Every third cycle	Depends on bias and test voltage ^b

^aNo-clean processes shall be tested at 40°C and 93% RH

^bThree test conditions are suggested with the following bias/test voltage/test frequency: 50 V/100 V/24-96-168 h, 100 V/100 V/twice daily and 5 V/5 V/every 20 min

^cTo be specified in procurement documentation

10.6.3 Test Methods for Evaluation of Performance in Field Conditions

It is stated in IPC-9201 that SIR testing has been used as a predictive tool for estimating service life [2] and in Appendix C to IPC J-STD-001D that the intent of the testing is to show that a proposed manufacturing process change can produce hardware with acceptable end-item performance [29]. To my knowledge, the results from SIR testing have never been correlated to field performance. Field conditions are usually quite different from the conditions used in the tests. For most products, exposure to humid conditions will be followed by dry-up periods, which will affect especially electrochemical migration. More important, although the test conditions may seem severe, many field conditions are considerably harsher than the test conditions. If condensation occurs on a biased non-coated assembly, short circuits due to ECM will normally occur within a few minutes even if the assembly is clean. Although IPC's Test Method 2.6.3, Class 3 is specified to be used for condensing service environment, condensation of water does not normally occur in the test when free-standing assemblies are tested. Furthermore, in many environments, and especially when forced-air cooling is used, assemblies will be contaminated with fibres, dust and particles from the environment [26]. Many of these contaminants contain hygroscopic and/or ionic compounds which will degrade SIR and the resistance against ECM. Corrosion of metallic surfaces due to corrosive gas pollutions may also affect SIR and ECM. All these parameters must be considered when assessing how the service life will be affected.

The problem is how to assess how the conditions in the field environment will affect SIR and the risk for ECM. No studies, to my knowledge, have been performed of how dry-up periods affect SIR and dendrite formation. A test method for contamination with ammonium sulphate particles has been developed by AT&T Bell laboratories [51] which could be used to study the impact of ionic contamination from the field on SIR and ECM but that has not been done so far. During the eighties, test methods were developed for evaluating the impact of corrosive gas pollutions on the reliability of connectors [26, 52–54]. These could also be used for evaluating the impact on SIR and ECM.

10.6.4 Acceptance Criteria

Even if the knowledge of how to adequately test SIR and electrochemical migration is far from satisfactory, relatively much has been written about the subject compared to what has been written about acceptance criteria.

There are two aspects on SIR requirements. First, a certain level of SIR is required for the proper function of a PBA. Second, a certain level is believed to be needed in order to avoid electrochemical migration, although this is not well

understood. However, there is no standard that makes any distinction between these two aspects, and thus it is not clear to which aspect requirements refer. Obviously, in the first case, the required SIR may differ considerably between different products even if they will be used in the same environment and, therefore, acceptance criteria have to be application specific. The required resistance to avoid dendrite formation will probably be less dependent on the function, i.e., in the second case, the required SIR will be the same for products that will be used in similar environments. However, since humidity and contamination levels in the field environment will have a very large impact on both SIR and ECM, it will be necessary to have different acceptance criteria for various types of applications also when considering the risk for electrochemical migration.

10.6.4.1 Acceptance Criteria for SIR

A low SIR may alone be the cause of failures but the SIR level at which failures will occur depends on the electrical requirements of the circuitry. Thus, SIR measurements are useful for verification of the performance of a printed board assembly, but SIR should then be measured directly with only a short stabilisation period in order to avoid a drift of the measured SIR value. The drift of SIR during measuring and the influence of previous measurements on later measurements may be avoided by using an AC voltage at a low frequency of about 1 Hz [22]. Very little has been done in this field but it may be the most relevant method for SIR measuring, and efforts ought to be made to investigate this alternative more deeply.

As already discussed, SIR is to a very large extent affected by humidity, temperature and contaminants. Especially, hygroscopic contaminant may have a large impact and can cause a sudden drop in SIR when the relative humidity surpasses the critical humidity at which the contaminant becomes hygroscopic. Hence, an informative test would be to screen the relationship between SIR and the relative humidity in order to detect the presence of hygroscopic contaminants and determine critical relative humidities. Since the critical relative humidity decreases for many substances with increasing temperature (see Table 10.1), this screening should preferably be performed at both a low and a high temperature. However, since some residues may be decomposed or evaporated at high temperatures, for example adipic acid and polyethylene glycol, extended exposure to high temperatures should be avoided [55].

A good example of a function-based, application-specific requirement has been described by Mason [11]. The company's most sensitive circuit had a device with 0.5-pA maximum offset current. Two guard tracks are used, each 25 mm long and separated from the guarded track by 1.25 mm. The potential between guarding and guarded tracks was 15 mV. Hence, the minimum required SIR was 3×10^{10} ohms or 1.2×10^{12} ohms per square.

10.6.4.2 Acceptance Criteria for ECM

Although it is not explicitly expressed in the tests for SIR and ECM testing, it can be assumed that specified acceptance criteria have been set based on the risk for ECM even when they are called SIR tests.

Most SIR and ECM standards have numerical requirements. The requirements usually differ between various standards. Even if the numerical requirement of the SIR is the same, the test conditions may vary which, in practice, means differing acceptance criteria. Usually there is a requirement that SIR shall not be less than a certain value. Some electrochemical migration tests also require that SIR not decrease more than one decade during the test [49]. Due to the experience that dendrites normally form without any impact on SIR, some later standards also have visual requirements regarding presence of corrosion, dendritic formation and mealing of conformal coating [29].

IPC's standard for soldered assemblies, J-STD-001D [29], is a good example of the many uncertainties that arise when one tries to get a grip on the basis for the acceptance requirement. In Appendix C, the acceptance requirement is that the SIR value shall be not less than 100 Mohm. It is specified that the test pattern must provide for SIR testing similar to that of the IPC-B-36 circuitry which is a leadless ceramic chip carrier with 68 castellations (open circuit) mounted on a pattern with interdigitated solder lands. Components of the type to be soldered in production representative of the "hardest-to-clean" configurations shall be included on the printed board assembly. Then, what does similar circuitry mean? The most likely interpretation is components with open circuit mounted on patterns with interdigitated solder lands. However, any change in the number of connections and/or pitch for a test pattern will, of course, influence the measured SIR and the acceptance criterion ought to be adjusted but nothing is mentioned in the standard about how to deal with that. Ideally, this can be handled using the ohms/square concept [6]. However, since SIR does not follow Ohm's law and contamination is not usually uniformly distributed across the entire test pattern, it is stated in IPC-9201 that normalisation of resistance to an ohms/square value is a questionable practice [2]. Thus, the question remains how to adjust the acceptance criterion in J-STD-001D to differing test patterns.

Furthermore, the reason for setting the acceptance criterion to 100 Mohm in J-STD-001D is not given. When looking in previous IPC standards, it can be noted that acceptance criteria for SIR tests usually are chosen in the range of 100-500 Mohm, although the test conditions and the test pattern may vary considerably. In an IPC technical paper from 1985 [56], it is mentioned that the practice at that time was to require a SIR of 100 Mohm but then only as a requirement for initial resistance. When testing according to J-STD-001D, one can choose between two test methods, one static for non-condensing service environment and one cyclic for condensing service environment. The static test method has requirements for SIR after 96 and 168 h of testing, whereas the cyclic test method has requirements for SIR only after 160 h of testing. There is a tremendous difference between specifying requirement for initial SIR compared to after 100-168 h testing.

As shown by Chan [22], SIR may increase several decades on a contaminated board during a test period of 100 h and approach values of a clean board. Thus, it seems odd to disregard from initial measurements and have requirements on SIR only after some days of measuring, as several standards have. Since no information is given on the background to the SIR requirements in J-STD-001D, it is not possible to draw any conclusion about the relevance of the requirements, nor to justify the disregarding of initial SIR values. The correlation between low initial SIR values and the risk for the dendrite formation needs to be explored more deeply.

It can be noted that the newly developed test for surface insulation resistance of assemblies in IEC standard 61189-5 [50] does not contain any acceptance criteria at all. It only specifies how the test should be performed, how it should be evaluated and what the test report should contain.

References

1. Ellis BN (1994) The determination of flux residue safety: the state of the art. *Circuit World* 20(4):26–32
2. IPC-9201 (1996) Surface insulation resistance handbook. IPC <http://www.ipc.org>
3. IPC-TR-476A (1997) Electrochemical migration: electrically induced failures in printed wiring assemblies IPC. <http://www.ipc.org>
4. Ellis BN (1995) On insulation resistance. *Circuit World* 21(2):5–18
5. Osborne AG (1983) Modern thoughts on surface resistance. IPC technical paper IPC-TP-498
6. Gorondy EJ (1984) Surface insulation resistance (SIR) part I: the development of an automated SIR measurement technique. IPC technical paper IPC-TP-518
7. Tegehall P-E, Dunn BD (1992) Influence of flux residues and conformal coatings on the surface resistance properties of spacecraft circuit boards. *ESA J* 16(3):255–273
8. Yan BD, Meilink SL, Warren GW, Wynblatt P (1986) Water adsorption and surface conductivity measurements on α -alumina substrates. In: proceedings of 36th electron compon technol conf, pp 95–99
9. Grossmann G (1996) Contamination of various flux/cleaning combinations on SMT assemblies: a discussion of different analysis methods. *Solder Surf Mt Technol* 22:16–21
10. Gorondy EJ (1988) Surface/moisture insulation resistance (SIR/MIR): part III analysis of the effect of test parameters and environmental conditions on test results. IPC-TP-825
11. Mason BJ (1994) No-clean flux appraisal—the total process approach. *Circuit World* 20(2):21–32
12. Alder JF, Isaac CA (1971) Constant humidity. In: Weast RC (ed) *Handbook of Chemistry and Physics*, 52nd edn. The Chemical Rubber Co., Cleveland, p E-40
13. Wexler A (1995) Constant humidity solutions. In: Lide DR (ed) *Handbook of Chemistry and Physics*, 76th edn. CRC Press, Boca Raton, Florida, pp 15–23
14. Anderson JE, Markovac V, Troyk PP (1988) Polymer encapsulants for microelectronics: mechanisms for protection and failure. *IEEE Trans Compon Hybrids Manuf Technol* 11(1):152–158
15. Brous J (1981) Water-soluble flux and its effect on PC board insulation resistance. *Electron Packag Prod* 21(7): 79–87
16. Adams KM, Anderson JE, Graves YB (1994) Ionograph sensitivity to chemical residues from “no clean” soldering fluxes: comparison of solvent extract conductivity and surface conductivity. *Circuit World* 20(2):41–44

17. Benson RC, Romenesko BM, Weiner JA, Nall BH, Charles HK Jr (1988) Metal electromigration induced by solder flux residue in hybrid microcircuits. *IEEE Trans Compon Hybrids Manuf Technol* 11(4):363–370
18. Zou L, Hunt C (1988) Surface insulation resistance (SIR) response to various parameters. NPL report CMMT(A)120. <http://www.npl.co.uk>
19. Warren GW, Wynblatt P, Zamanzadeh M (1989) The role of electrochemical migration and moisture adsorption on the reliability of metallized ceramic substrates. *J Electron Mater* 18(2):339–353
20. Steppan JJ, Roth JA, Hall LC, Jeanotte DA, Carbone SP (1987) A review of corrosion failure mechanisms during accelerated tests. *J Electrochem Soc* 134:175–190
21. Bumiller E, Pecht M, Hillman C (2004) Electrochemical migration on HASL plated FR-4 printed circuit boards. *J Surf Mt Technol* 17(2):37–41
22. Chan HA (1996) Is the current surface insulation resistance (SIR) methodology appropriate to today's manufacturing technology. In: proceedings of 46th electron compon technol conf, pp 234–241
23. Sohn JE, Ray U, Heideman V, Schubert B, Anderson JE, Adams KM, Becka G (1994) How clean is clean: effect of no-clean flux residues and environmental testing conditions on surface insulation resistance. In: proceedings of Surf Mt Int: 1994 391–402
24. Hunt C, Zou L (1999) The impact of temperature and humidity conditions on surface insulation resistance values for various fluxes. *Solder Surf Mt Technol* 11(1):36–43
25. Zou L, Hunt C (2008) Electrochemical impedance technique to predict circuit reliability with lead-free solders. NPL report MAT 15. <http://www.npl.co.uk>
26. Tegehall P-E (1998) Reliability verification of printed board assemblies: a critical review of test methods and future test strategy. In: proceedings of Surf Mt 1998 Int 359–382
27. Tegehall P-E (1998) Impact of contamination from production processes on the reliability of printed board assemblies. In: proceedings of int conf electron assembly: materials and process challenges, pp 69–80
28. Sanftleben H (1996) Ionic cleanliness of LPISM circuit boards. *IPC Rev* 37(2):30–32
29. J-STD-001D (2005) Requirements for soldered electrical and electronic assemblies. [IPC](http://www.ipc.org) <http://www.ipc.org>
30. Ellis BN (1986) Cleaning and contamination of electronics components and assemblies. Electrochemical Publications, Ayr Chapter 15
31. Lea C (1989) Residues on soldered printed circuit assemblies. *Circuit World* 16(1):44–46
32. Dunn B (1980) The fusing of tin-lead plating of high quality printed circuit boards. *Trans Inst Met Finish* 58:26–28
33. Pauls D (2001) Residues in printed wiring boards and assemblies. *Circuit World* 27(1):32–41
34. Bulletti A, Capineri L, Materassi M, Dunn BD (2007) Surface resistivity of new printed circuit board materials for use in spacecraft electronics. *IEEE Trans Electron Packag Manuf* 30(2):115–122
35. Zado FM (1983) Effects of non-ionic water soluble flux residues. The Western electr eng, first issue, pp 41–48
36. Brous J (1992) Electrochemical migration and flux residues—causes and detection. In: proceeding of Nepcon West 386–393
37. Ready WJ, Turbini LJ, Stock BA, Smith BA (1996) Conductive anodic filament enhancement in the presence of a polyglycol—containing flux. In: proceedings of 34th IEEE Int Reliab Phys, pp 267–273
38. Sinclair JD (1987) Corrosion of electronics by ionic substances in the environment. In: proceedings of ASM 3rd conf electron packag mater prod corros microelectron, pp 145–154
39. Sinclair JD (1992) The relevance of particle contamination to corrosion of electronics in processing and field environments. In: proceedings of 2nd int symp corros reliab electron mater devices, pp 325–335
40. Sinclair JD, Psota-Kelty LA, Weschler CJ, Shields HC (1990) Measurement and modeling of airborne concentrations and indoor surface accumulation rates of ionic substances at Neenah, Wisconsin. *Atmos Environ* 24A:627–638

41. Sinclair JD, Psota-Kelty LA, Weschler CJ (1985) Indoor/outdoor concentrations and indoor surface accumulations of ionic substances. *Atmos Environ* 19(2):315–323
42. Sinclair JD, Psota-Kelty LA, Peins GA, Ibidunni AO (1992) Comparison of electronic equipment room and factory environments. *Atmos Environ* 26A:871–882
43. Comizzoli RB, Frankenthal RP, Lobnig RE, Peins GA, Psota-Kelty LA, Siconolfi DJ, Sinclair JD (1993) Corrosion of electronic materials and devices by submicron atmospheric particles. *Electrochem Soc Interface* 2(3):26–33
44. Test Methods Manual IPC-TM-650, Test Method 2.5.2 (1979) Surface insulation resistance of raw, printed wiring board material. IPC <http://www.ipc.org>
45. Test Methods Manual IPC-TM-650, Test Method 2.6.3F (2004) Moisture and insulation resistance, printed boards. IPC <http://www.ipc.org>
46. Test Methods Manual IPC-TM-650, Test Method 2.6.3.1D (2000) Moisture and insulation resistance—solder masks. IPC <http://www.ipc.org>
47. Test Methods Manual IPC-TM-650, Test Method 2.6.3.3B (2004) Moisture and insulation resistance—fluxes. IPC <http://www.ipc.org>
48. Test Methods Manual IPC-TM-650, Test Method 2.6.14A (1987) Resistance to electrochemical migration, polymer solder mask. IPC <http://www.ipc.org>
49. TR-NWT-000078, Issue 3, Method 13.1.5, Electrochemical Migration (1991) Generic physical design requirements for telecommunications products and equipment bellcore (now supplied by Telcordia). <http://www.telcordia.com>
50. IEC 61189-5 (2006) Test methods for electrical materials, interconnection structures and assemblies—part 5: test methods for printed board assemblies, test 5E02: surface insulation resistance, assemblies. IEC <http://www.iec.ch>
51. Frankenthal RP, Siconolfi DJ, Sinclair JD (1993) Accelerated life testing of electronic devices by atmospheric particles: why and how. *J Electrochem Soc* 140:3129–3134
52. Abbott WH (1988) The development and performance characteristics of mixed flowing gas test environments. *IEEE Trans Compon Hybrids Manuf Technol* 11(1):22–35
53. Gore R, Witska R, Chao J (1989) Corrosive gas environmental testing for electrical contacts. *Proc Holm Conf Electric Contacts*, pp 123–131
54. Zakipour S, Leygraf C (1986) Evaluation of laboratory tests to simulate indoor corrosion of electrical contact materials. *J Electrochem Soc* 133:21–30
55. Sohn JE, Ray U (1995) Weak organic acids and surface insulation resistance. *Circuit World* 21(4):22–26
56. Eisenmann ET (1985) On the utility of insulation resistance tests to assess the life performance of printed wiring boards. IPC-TP-542