Summary

Recently the topic Electrochemical Migration is being discussed often in the context of failures of electronic assemblies.

Electrochemical migration develops basically by limitation of moisture which deposits in the shape of a film on the surface of the electronic assembly and can lead to a polarization of the metallisation. This causes a metal hydroxide- or complex concentration and finally the actual bridging between two solder joints either by galvanic deposition or by the precipitation of the hydroxides or complexes as salts (staining). As humidity-conditioned failure, the electrochemical migration (a type of corrosion) hence diminishes the reliability and lifetime of the electronic assemblies and is mostly responsible for climate-related failures.

Typical error images which indicate electrochemical migration are remaining and temporary short circuits. Temporary short circuits usually lead to the failure of the electronics, as the system generally switches into failure mode. Remaining short circuits can contribute to the local overheating of the interconnect device, whereby the polymer material graphitizes or the electronic assembly can start to burn.

After all how exactly does electrochemical migration develop, how can the risks therefore be estimated and especially, how are they avoidable? The subsequent article explains the requirements and the developing mechanism of the electrochemical migration and discusses after all the different methods for prevention.

1 Requirements for the development of electrochemical migration

The basic factor for electrochemical bridging is the presence of moisture, as it establishes the creation of corrosion. Moisture can occur in two different ways on the electronic assembly, on the one hand by adsorbing moisture films on the top surfaces, on the other hand via condensation.

The necessary, critical air humidity for adsorbing moisture films depends hereby strongly on the surface energy and surface polarity, i.d. on the material, especially the solder resist mask and its filling degree. It is achieved often already at air humidities explicit below the dew point, thus the temperature difference at which the first water drops form on the surface. To enable corrosion processes, for instance film thicknesses of some monolayers are necessary.

Besides adsorbed moisture films, temperature change induced condensation can also lead to electrochemical migration. Compared to the moisture films the condensation focuses on the most heat-conducting position, so the metallisations or hygroscopic areas like contamination. In many cases, organic acids or halogenide salts as typical solder residues lower the dew point locally down to 60% relative moisture.
Another important factor is the used material. The sufficient number of layers for a moisture film composes e.g. on metals respectively metal-oxidic surfaces starting at a critical humidity of 60% - 70% RH (Relative Humidity) or on silica-filled solder resist masks. Similarly corrosive gases act like e.g. nitrogen compounds, H₂S and CO₂ which moreover dissolve in the moisture film. On aluminum oxide ceramics or unfilled non-polar solder resist masks these are achieved not until 90 % RH or beyond. On a Sn-metallised epoxy resin-substrate, thus the interconnect devices, the moisture absorbs at a constant climate favoured on the resin surfaces and is adsorbed as well as stored up to the partial pressure equilibrium.

In addition, a metallization respectively solder material must exist which enables electrochemical migration. This means that the material must exhibit an active area in alcaline electrolytes (see grey fields in figure 1). In distilled water particularly silver, copper, lead, tin and cadmium migrate for instance. The affinity for bridging hereby follows very distinctive the potentials of the galvanic series and the reduction of the passive material performance in the alcaline area. In contrast for example with nickel under condensed water conditions it does not come to migration or corrosion. The liability of an element for electrochemical migration is assessable by help of the pH-potential, so-called Pourbaix-diagrams.

![Pourbaix-diagram of water and tin](image)

**Figure 1:** Pourbaix-diagram of water and tin

Besides the moisture and the used material, primarily residues and contamination on the electronic assemblies influence the development of electrochemical migration. Condensation is then especially being fostered if hygroscopic flux residues, dust or salt crystals are existent on the surfaces which function as condensation areas respectively -nuclei for moisture and pollutant gases. Such contamination acts in addition to favourable circumstances for adsorption on the surfaces as moisture reservoir,
so that e.g. the otherwise fast ongoing re-drying of polymers is guaranteed by starting at relative humidities below 30 % RH.

2 The formation mechanism

2.1 Anodic metal decomposition

In consequence of the on the electronic assembly surface adsorbed moisture film, the surface resistance and with it the necessary insulation properties of the used solder resist mask or interconnect devices is dropped. From a critical film thickness the intrinsic conductivity of the adsorbed pure water film establishes the electrolysis respectively if also the contamination is solved with it, the protolysis of the so formed electrolyte. This directs to a local, strong alkalisation of the anode, i.d. voltage supply (VCC) or signal leading contacts. By increasing the pH-value, especially silver, copper, tin and lead, which are the most widespread metallisation elements, are polarized in an electrochemical active range.

As a result of the anodic area's proportional resolution of the shunt current between contact and ground, i.d. the ground contact, a high metal hydroxide concentration or according to the electrolyte a complex concentration arises which mainly disperses along the concentration gradient (see figure 2).

![Figure 2: Formation of concentration profile at the begin of precipitation of a cathodic anodic growing dendrite](image)

The kinetics of the dissolution occurs via direct decollation from the atom site, from the edge position at on the surface escaped dislocations and at surface defects or via adsorbed so-called ad-atoms during continuous hydration.

The affinity for bridging must be seen in context with the solution- or solvation ability of the respective ions. For the migration of silver, the in aqueous media easily building and very well soluble Ag(OH), for instance, is sufficient. Gold however dissolves
only if a tetrachloridic gold complex can be created. This indicates that some elements at pure water conditions do not develop bridging, respectively, not until by contamination is the affinity for migration strongly increased.

2.1 Migration of metal ions

Apparently the migration of dissolved metallisation ions is then defined only by the adjacent electrical field if the conductivity of the electrolyte is dependent solely on the ions of the metallisation and not on the rate of the contamination. This condition is fulfilled as long as the concentration of the existing contamination which is dissolved on the electronic assembly, does not exceed in the magnitude of the concentration of the migrating metallisation ions.

The migration of the ions is determined thereby by the potential gradient and the concentration gradient. The potential gradient is assigned by the adjacent operating voltage and the conductor spacing, the concentration gradient by the dissolution- and the diffusion velocity of the solvated metallisation material ions, whereas the mobility of the ions is significantly dependent on the diameter of the complexes after the solvation, as well as the dissolving rate on the signal- respectively stand by-electric current and the active area.

Is the potential gradient small compared to the concentration gradient of the migrating ions, so the ions diffuse along the concentration gradient. Is it adequate big, it even can turn up to a migration of ions against the electrical field from the ground to the contact.

2.3 Deposition of metal ions

The actual bridging occurs indeed either by galvanic deposition, starting from the cathode (GND) or more seldom by the precipitation of the hydroxides or complexes as salts, the so-called staining from the anode (VCC or signaling contact).

The galvanic deposition takes place preferential at areas of high field strength. Are small solution conductivities upon lower ion concentration available, the field lines compress together at the top and edges. This leads to the development of surficial lattice distortions at the solder joints or VCC-metallisation to micro roughness and via pyramidal growth to the formation of dendritic structures. Are high ion concentrations or -gradients existent, so smoother growth structures are preferred. Ribbons or fibre strands start to develop (figure 3).

The velocity with which the bridging occurs, can be diminished by bigger and directed grains at the solder joint thus via the soldering profile. The bigger grains cause a decline of the void number as they import grain boundaries. Thus here is a conflict of aims existent with the mechanical stability of the solder joints, because for this purpose fine graininess is pursued.

It comes to staining if the solubility of the hydroxides or complexes is exceeded in the adsorbed moisture- or condensation film and these dissipate as salts e.g. tin adipate. With galvanic deposition it is expected that the bridges are mainly metallic assembled. For staining the composition of the bridges depend on the electrolyte, as here metal salt- or complex compounds are being generated.
The migration bridges can span distances on the surface like as well in the inside of fibre-reinforced base materials up to several millimeters. Do the dendrites run across the fibers in the base material the electrochemical migration is named CAF (Cathodic Anodic Filament Growth).

2.4 Assignment of electrochemical migration to other dendritic failures

To approach a targeted causation relief for failures, it is important to differ the electrochemical migration from other failure mechanisms with dendritic appearance. Here especially have to be named electrical breakdowns and graphitisations on devices like barium titanate capacitors.

Electrical breakdowns are caused especially by pores or blisters in the solder resist, more rarely in protective varnishes or potting compounds. The reduced insulation capability can be further depreciated by inclusions of moisture. Here the porosity must be tackled causative by optimizing the solder resist application.

According to the quality standard also ceramic capacitors with organic coatings appear on the market, whose insulation efficiency can be too small for the case of operation. Then again tree-like graphitisations develop here as with the porosity in the solder resist caused by electrical breakdown. Experiences in the field point out that a certain degree of coating provides a beneficial influence for stabilizing against electrochemical migration, as these layers are mostly hydrophobic. As research studies by Matzner have shown, again the geometry of the capacitors plays here an important role.

3 Consequences of electrochemical migration

Often the electrochemical migration ECM is not or only with great effort verifiable as root cause for damage or dysfunction. If after short condensation times of typically a few minutes only small dendrites appear, then these are not able to conduct electricity and burn down again immediately. This leads to high dissatisfaction of the end user, as well as to the damage of one's image and depending on the application to high consequential costs after the failure. For proofing the electrochemical migration, the
affected circuits must be returned from the field and examined in the scanning tunnelling microscope for ECM marks. Unfortunately, even from the logistical point of view it is often not possible. Therefore these failures are found again in unspecific manner together with software bugs and creepage defects as malfunction.

During the creation of consisting so to speak current conducting dendrites quickly temperatures of 600°C and more occur (figure 4).

![Figure 4: The formation of yellow and red tin oxide is a sign of too high temperatures](image)

If so the circuitry does not come with an appropriate protection and shutoff these temperatures lead to burning. As hereby the circuitry is being destroyed, it persists in many cases speculative, whether the cause for burning is the result for electrochemical migration or e.g. the electrical breakdown. Fires of vehicles to wind energy plants are damaging the image to the highest grade, hence always picked up likely by the press.

4 Measurements for avoiding/prevention

Are the possible consequences being considered of electrochemical migration, so someone can raise the question, how the migration can be avoided.

As already mentioned at the beginning the material has an influence on the creation or favouritism of electrochemical migration. Therefore as protective measurements is to mention an appropriate selection of materials for use as well as a non-sensitive circuit design.

A selection of materials with regard to a hydrophobic, so then mostly unfilled solder resist mask which minimizes the adsorbed moisture film, shifts e.g. the critical moisture film to higher relative humidities in the direction of condensation.

A metallisation would be for recommendation which creates only difficult soluble complexes and ideally in the alcaline area no hydroxides. Nickel or nickel gold metal-
lizations on the bare board side and Ag-free solder against the soldering trend would have an beneficial effect. Just the already in thin moisture films from 60% RH on well soluble silver hydroxides carry an especially high risk.

By making use of the electrical design it is only limited possible to preclude against electrochemical migration in contrary to the threat of parasitic creepage currents. Short signal times, thus high-frequent signals reduce the risk based upon the dullness of the corrosion processes. Also by using active components with lower input impedances the affinity of short time consistent bridges increases to have a technical breakdown. Low resistant components develop during operation as well as higher heat losses, whereby self-drying and as such an intrinsic safety of the circuitry is achieved. However on the other hand high losses should be avoided especially for mobile battery-buffered systems upon the restricted battery demand. Also the separation of power supply/VCC and ground/GND is mostly in the conflict of objectives with electromagnetic radiation requirements/EMI.

So essential the lever of the materials and the circuit design still appears, so low is the chance in reality to change something at an existing product, because many other factors play a role here.

An often used method for the assumed prevention of electrochemical migration is hence the coating. It is commonly accepted that the coating provides a reliable protection against moisture and as such obviates electrochemical migration as main cause. Indeed coatings are not 100% impermeable against moisture. Assuming from the pure theoretical consideration that the electronic assembly is absolutely clean before coating, so the coating would serve the purpose. Moisture in fact could diffuse through the coating, but would not have the possibility to condensate on the surface of the electronic assembly but would remain in the varnish and could not harm from this point.

However in practice it has been coated during no clean-processes without making sure beforehand the necessary surface cleanliness. Not seldom increased surface thicknesses are used by thinking from the security point of view, following the well-known slogan “Two are better than one”, or in this case: Thicker is better than one. But as long as contamination is present on the electronic assembly surface, the protection against electrochemical migration is a false conclusion.

The after the solder process remaining residues like e.g. fluxes, activators and resins as well as dust and salt crystals which can be existent on the surfaces, function as condensation nucleus and moisture storage and besides stimulate the creation of soluble metal complexes. Is moisture permeating the coating it can condensate at the contamination and finally leads to electrochemical migration under the coating. Therefore a reliable protection against electrochemical migration is only achievable by combining cleaning and coating. Optimally adapted cleaning processes to the particular electronic assemblies and the subsequent coating guarantee residue-free surfaces. This raises not only in many cases the coating adhesion and quality, but secures that moisture remains in the coating and cannot condensate, so that electrochemical migration is fundamentally prevented.

5 Conclusion

Various factors are responsible for the development of electrochemical migration. Usually it is hereby not possible for the user to control or change all factors accordingly as e.g. the used materials. Also the estimation of the risk is difficult to comply with in each case upon the complexity of the mechanism. A coating alone does not
protect in every case against electrochemical migration. To prevent reasonable and secure, it can happen however by implementing a cleaning process before coating. While looking for the right cleaning process ZESTRON supports you willingly with cleaning trials in the Technical Centers, followed by an analysis of the results immediately. Furthermore it could be proven within another study that according to the consisting cleaning process, another purification process could be implemented in the production without increasing the total costs, while simultaneously the coating process would be optimised and the reliability would be augmented.