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Technical Notes

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Protection from the Elements Part III: Corrosion of Electronics

This Technical Briefing Note examines corrosion mechanisms common to electronic assemblies and summarizes conformal coating and potting technologies used to mitigate corrosive action in finished pico-powered lighting assemblies

Information contained in this article builds on previous Technical Notes available on the Lighting Global website.

Introduction

The environmental stresses placed on pico-powered lighting products are often fairly extreme. Most are designed to see daily exposure to intense sunlight and the associated thermal cycling. They are often mobile devices and will continually be moved from one location to another with the very real possibility of regular drops and spills. They get dirty from ground contact and rough handling, and many will be exposed to water in the form of rainfall, moisture in the air, and groundwater contact.

The electronic nature of pico-powered lighting products coupled with their typical service environment creates an atmosphere that can be very conducive to corrosion. The batteries, electronic circuit boards, LED lights, and multiple external connectors (for wires between product components) are all potentially vulnerable. The failure mechanisms described in this article are known to affect electronic devices in circumstances similar to those seen by pico-powered lighting products, but it is not known if devices in the field have seen all of these types of failure.

Catastrophic and Corrosive Failure modes

Any event that causes a product to stop working can be considered catastrophic. For the purposes of this discussion, catastrophic failure modes are ones that immediately or very quickly cause the product to fail. A failed drop test is a good example of a catastrophic failure – the product may stop functioning if dropped onto a hard surface because a wire solder joint detaches from the printed circuit board (PCB) inside the enclosure. Another example might be related to physical ingress, where a stick or sharp object enters the housing and destroys the small lens on the LED package, killing the light output instantly.

Water exposure, on the other hand, may or may not cause catastrophic failure. Water does not immediately destroy all electronics or electronic devices. Cell phones tend to catastrophically fail after one full submersion (due to damaged suffered by the sensitive screen elements), but many pico-powered lighting products will continue to function immediately after electronics are placed in water. This may not be true for prolonged or repeated exposures, however, as the combination of water and charged electrical circuits tends to promote corrosion and is certainly capable over time of destroying circuit (and product) functionality. Whether a product fails in this circumstance depends on a number of variables including the degree and location of water exposure, duration, temperature, and the voltage difference of adjacent conductors.

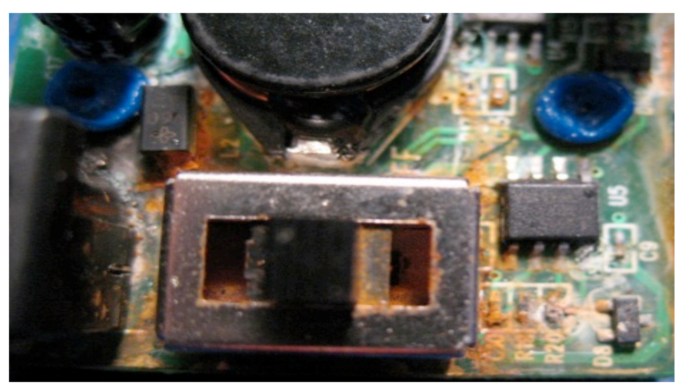

Figure 1. Corrosion on a Lighting Africa test product

Electronic Corrosion mechanisms

There are several corrosion mechanisms common to electronic assemblies. Corrosion occurs in a variety of conditions where metals are exposed to humidity and water, and some corrosion mechanisms are made worse by the presence of low voltage electric potentials between adjacent metal surfaces. The time required for corrosion to affect a product is highly variable and a result of many environmental, temperature, and exposure factors. Some of the following corrosion mechanisms have been observed directly in pico-powered lighting products tested by Lighting Global while others are known to occur in electronics generally but have not been confirmed in tested products.

Electrolytic corrosion

This type of corrosion typically presents the greatest risk of damage to pico-powered lighting products. **Electrolytic corrosion is caused by small electric currents that flow between adjacent metal conductors in the presence of an applied voltage and a liquid electrolyte** (Figure 2).

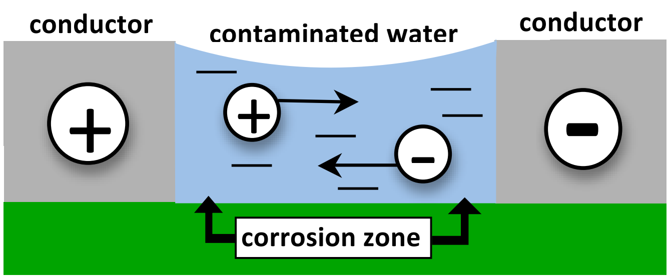

Figure 2. Electrolytic corrosion diagram

The metal conductors serve as the two electrodes in an electrolytic cell, and small water droplets and surface water vapor can function as the electrolyte. Metal ions from one electrode (the anode) dissolve in the electrolyte and are deposited on the adjacent electrode (the cathode)(Figure 3). The water in the cell must have ionic components necessary for the reaction. These "contaminants" often come from the processing and handling of the circuit board or are byproducts of other

Figure 3. Electrolytic corrosion of a Lighting Global test product. The anode is preferentially corroded as metal ions enter an electrolyte solution formed by water vapor between the LED leads. The leads are tin plated steel as evidenced by the iron oxide stains on the anode and electrolyte path on the PCB.

product assembly steps and subcomponent materials. Sources of contamination include flux residues, cleaners, processing gases, coatings, and many circuit handling steps where salts, acids, and other ionic elements have access to the board and components.

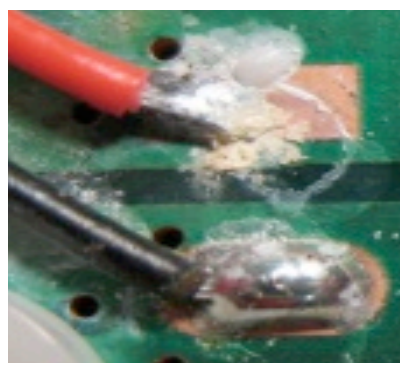

Figure 4. Corrosion on the anode solder pad under a conformal coating. Note the incomplete coverage of the solder on the pad

Manufacturers may be tempted to encapsulate, coat, or insulate specific anodic points in their assemblies to prevent metal ions from entering solution. This approach should be handled with caution, and specific testing should be performed, as any defects in the coating and anode exposure can lead to highly accelerated local corrosion of the anode if an electrolytic path is available for the reaction (Figure 4). Identifying the electrochemical anode can also be confusing. A battery in the system can have one battery terminal OR the other serving as an anode depending on whether the battery is charging or discharging.

Galvanic corrosion

Galvanic corrosion, distinct from electrolytic corrosion, occurs when two dissimilar metals come in contact with one another in the presence of water (Figure 5). This can occur with solder joints, on plated conductors, and can be particularly problematic on conductors used in switches and plug contacts.

The two dissimilar metals in the galvanic cell create a natural voltage potential which can drive the corrosion process – no externally applied voltage is necessary. Again, an electrolyte with ionic conductors is required, and this can come from water vapor, condensation, and water immersion of the conductors.

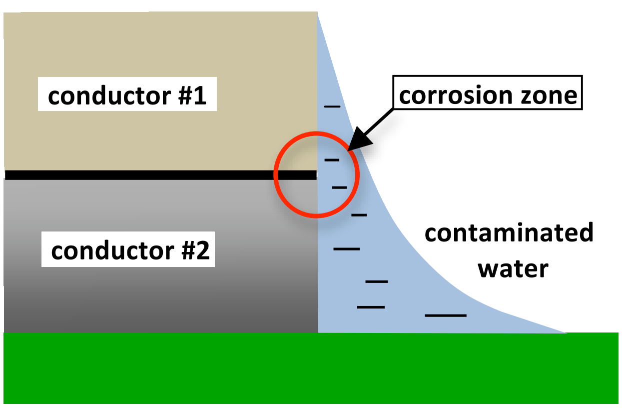

Figure 5. Galvanic corrosion of dissimilar metals

Electro chemical migration

Electro chemical migration occurs when thin conductive dendrites form across adjacent conductors, shorting the connection. This can occur in an electrolytic cell formed between adjacent pins on an integrated circuit (IC) package, or between thinly spaced copper circuit lines. Dendrites can form from silver, copper, tin, lead, or a combination of metals, and growth rates can be quite high. Failures from dendrite growth can occur in less than a day under the right environmental conditions and circuit layout (Figure 6).

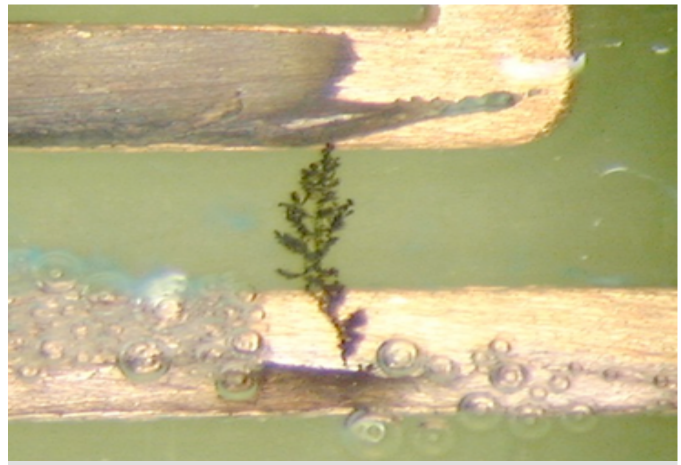

Figure 6. A conductive dendrite short circuit underneath conformal coating.

Creep Corrosion

Creep corrosion forms from copper sulfide oxidation products on the surface of a PCB. The oxide layer can form on top of the solder mask and is typically seen in environments with elevated sulfur levels (Figure 7).

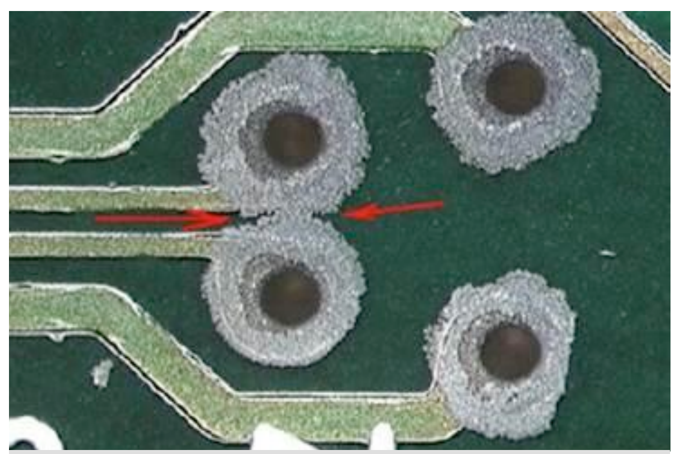

Figure 7. Creep corrosion of PCB vias

Fretting Corrosion

Fretting corrosion affects non-noble electrical contacts (especially tin) undergoing small cyclical oscillations caused by vibrations at the metal-metal contact surfaces. These small oscillations break apart the oxides that naturally form on the metal, and because the relative movement of the opposing surfaces is very small these oxides can build up between the contacts and lead to an increase in the contact resistance. The normal wiping action of plugging/unplugging the contact will typically clear the oxides away, but this corrective measure is not available for internal wire-to-wire or wire-to-board connectors. Using noble metal (e.g. gold-plated) contacts or high insertion force contacts (where the mated parts are held firmly in place) will prevent most cases of fretting corrosion.

Tin whiskers

The advent of lead-free technologies also gave rise to an increased risk for the formation of tin whiskers. Although not a form of corrosion, tin whiskers nevertheless behave in much the same way as some corrosion mechanisms. Very thin, hard whiskers are known to grow on component leads that are tin- plated (Figure 8). These whiskers are thought to arise as a reaction to surface compression stress in the pure tin coating and can short circuit adjacent leads.

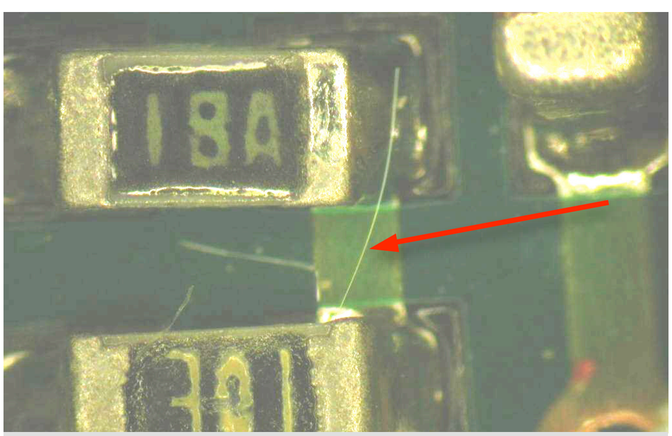
Figure 8. Tin whisker forming between resistor pads

Water contamination and ionic content

Water is a key driver of corrosion in electronic circuits. Water can reach sensitive circuit elements from external exposure (i.e. rain or water can enter the product housing), water droplets can condense in the humid environment often found inside these types of products, and water vapor can be absorbed by dirt and dust on the surface of circuit boards and exposed metal connectors and initiate corrosion that would otherwise not occur on a clean circuit board.

Small concentrations of various contaminants are typically all that is required to allow water to serve as the electrolyte in a corrosion process. These contaminants often come from the processing of the product during manufacture and assembly, either from intentional exposures to process gases, solvents, plating solutions, polymer formulations, and soldering flux residues, or through incidental contact with workers or customers handling and using the product.

Acidic and organic contaminations are particularly damaging and can greatly accelerate corrosive activity and corrosion rates. Aggressive ions from process steps will often leave residues, even after cleaning. Chlorides, sulfur compounds, salts, and any chemicals capable of producing ionic (charged) compounds will increase the corrosive action of the water electrolyte.

Proper cleaning and processing of product components is helpful in lowering the electrolytic content of water exposures. However, since very small contaminations are enough to enable corrosion, it is typically not sufficient (or wise) to rely on a clean circuit board to prevent corrosion upon exposure to water (which may itself already have enough ionic content to serve as an electrolyte).

Battery terminals

Protecting batteries and battery terminals from corrosion can be challenging. Battery contacts and wire leads will often present ideal locations for corrosion because of the applied voltage and water trapping features of the physical assembly (Figure 9). Contacts have multiple types of metals and plating finishes with galvanic potentials. Attempts to insulate the exposed surfaces can leave small spots unprotected and lead to accelerated localized corrosion. Some battery types can vent corrosive gases during charge/discharge cycles.

Figure 9. Early signs of corrosion on battery leads

Protecting against corrosive failures

Designing an inexpensive pico-powered lighting product that can tolerate exposures to sunlight, dirt, humidity, rain and frequent rough handling is a difficult engineering task. Each component must be matched to the others in the system, and all must work together to achieve the goal of continued functionality. No product will last indefinitely, but proper design choices can help avoid problems that arise as a result of harsh environmental exposures.

Material compatibility

The various materials used in the product housing and internal components must be compatible with each other. Some plastics used for the product housing will continue to off-gas elements that can accelerate corrosion. Vinyl (PVC) based materials, for example, can emit chlorine gases and other volatile organic compounds (VOCs) that can be a source of contamination for electrolyte formation on the internal circuit boards. This can be a problem with very new parts used in the assembly that have not had time to off-gas VOCs after injection molding.

Coatings and finishes must also be compatible to achieve good adhesion. Cleanliness is once again extremely important in assuring that materials behave according to design. Process residues must be controlled and proper handling assured throughout the manufacturing and assembly process.

PCB finishes

Circuit traces are made of copper. Boards are covered with a solder resist (solder mask) on top of the traces and plated with various finishes to protect the bare copper pads prior to component assembly and aid in soldering during reflow.

Once assembled the PCB pads are covered by the component leads and solder. The plating may dissolve in the solder and/or form various alloys at the junction that will have some type of galvanic structure. Vias and other board details, however, are not soldered and may have areas where the board finish is exposed.

Lighting Global does not have clear evidence suggesting which board finishes will protect a pico-powered lighting product from corrosion. Immersion tin (ImSn) and lead-free hot air solder leveled (HASL) finishes contain tin that can protect the underlying copper. Gold finishes (ENIG, NiAu) resist oxidation but can also form strong galvanic couples. Gold finishes are expensive, however, and immersion tin may be prone to tin whiskers. Organic solderable coatings (OSP) and immersion silver have been linked to creep corrosion in high sulfur environments. Manufacturers are encouraged to investigate the use of different PCB finishes to increase corrosion resistance and product lifetime.

Conformal Coatings

Conformal coatings can be applied on an assembled PCB to protect the underlying components from moisture, dirt, vibration/impact, and temperature extremes. There are several different types of conformal coating materials and application procedures (Figures 10,11). Each has advantages and disadvantages in different environments as well as cost implications. Standards for conformal coating technologies can be found in IEC 61086-3-1, IPC-CC-830B, MIL-I-46058C, UL746E, and UL94

Types of conformal coatings

Acrylic (Type AR) – Acrylic formulations have good moisture resistance and offer ease of repair/rework. They are inexpensive and the most common type of coating used for consumer electronics.

Epoxy (Type ER) – Epoxy formulations provide excellent abrasion and chemical resistance, but poorer moisture and dielectric performance. Epoxies are virtually impossible to remove for rework due to the other epoxy based materials on a board (epoxy glass substrate and epoxy based plastics in component housings), which can be vigorously attacked by the application of an epoxy based stripping agent.

Urethane (Type UR) – Urethane formulations provide excellent chemical resistance combined with good moisture, temperature and dielectric properties. The high level of chemical resistance, however, can make rework difficult and costly.

UV Curable (UV) Ultraviolet light curable coatings offer extremely fast cure speed and low VOC content as well as providing excellent moisture, dielectric, temperature resistance and chemical resistance. UV curable materials are particularly suited for high volume, selective coating applications.

Silicone (Type SR) – Silicones have high and low temperature capability and have very good adhesion to the substrate. Available in soft formulations that have good stress relieving qualities.

Parylene (Type XY) – Sometimes referred to as a gold standard, the deposition process uniformly covers all component edges and pockets with a durable, highly resistant coating. Parylene is the most expensive coating type.

Figure 10. Conformal coating application methods

All conformal coatings are permeable to air and water vapor to some degree. With the exception of parylene, the coatings do not serve as a true water barrier but rather limit the access of water molecules to ionic contaminants that may then act as the electrolytic transport components in a dynamic corrosion reaction. This is particularly important in situations where the coating adhesion to the substrate fails and an electrolytic reaction occurs underneath the coating.

Application techniques

Spray – Multiple spray passes at different angles are necessary to cover components and avoid shading.

Dip – Provides good coverage under and around component leads, but not available for all coating types.

Brush – Good for low volume and selective coating on the PCB, but is prone to coverage errors and requires trained personnel to avoid problems.

Figure 11. Conformal coating application methods

Cleanliness is critically important to achieving good adhesion between the coating and PCB substrate and avoiding problems with corrosive failures (Figure 12)***.***

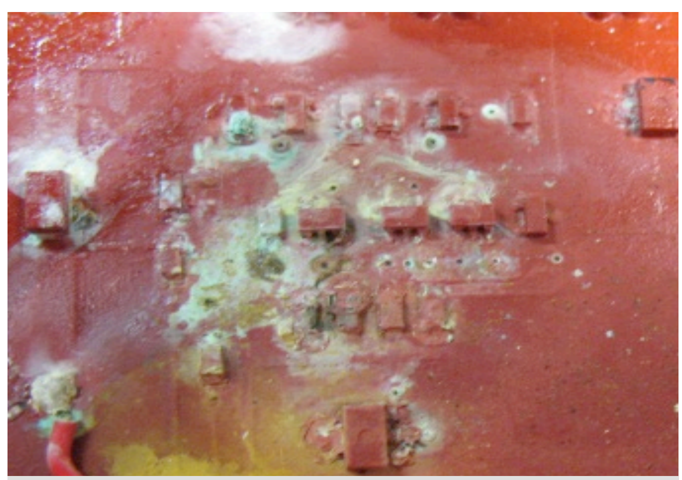

Figure 12. Corrosive failure on a coated PCB

Important factors in choosing a conformal coating

Cost - Costs vary by material choice and application technique. Acrylic is typically the least expensive (and very common for these types of applications) while parylene is the most expensive due to the vapor deposition application process.

Environmental protection - For pico-powered lighting products, moisture (from humidity and rain) and elevated temperature (~50 C) are likely to be the primary environmental threats. Under some design circumstances UV exposure may also be an issue. Many coating manufacturers suggest that their products will help protect PCBs from humid environments but may not provide adequate protection from direct liquid water exposures and submersions.

Application technique - Spray, dip, brush, and vapor deposition (Figure 10). Some application techniques are not available for all coating types.

Coverage – Proper coating thickness is essential for protection. Too thin or too thick coats will exhibit service problems. Pinholes, bubbles, wrinkles, and delamination of the coating must be avoided. Liquid coatings have trouble covering sharp edges on components and any solder spikes where the coating tends to thin out due to surface tension. This is known as "edge crawling" and can be avoided with multiple thin coats and careful attention paid to the coating viscosity to maintain adequate thickness.

Conformal coatings are usually applied to a circuit board that has selective areas masked off. External connectors and wire-to-board solder pads are often used during assembly ***after*** the conformal coat is applied, and unless follow-up protection is provided to these areas (e.g. encapsulation, see below) they may be at increased risk as possible corrosion sites.

Rework/repair - Some coatings are easier to rework than others. The coating may need to be chemically or mechanically removed prior to rework and subsequently reapplied. Some coatings allow solder joints to be burned directly through the material.

Curing systems

Conformal coatings must be properly cured after application. Some coating systems use a two-part mixture that cures through a chemical reaction, others are a single component that cures with exposure to heat, atmospheric moisture, or UV exposure.

Problems can arise from improper curing of the coating. Some process contaminants or component materials can inhibit the cure of two part systems. Tall components can shield the underlying coating from UV curing lamps, and improper thermal cycling can leave some areas uncured.

Conformal coatings, wires, and connectors

Wire-to-board solder joints and board-mounted plug, headers, switches, and connectors are problematic when used on conformal coated circuit boards. Wire to board solder joints can flex when the wires flex, breaking the coating and/or serving as moisture entry points for water that travels along wires and collects at the joint. When applied after the conformal coat, solder joints will not be protected unless additional encapsulation is performed.

Plugs and switches that are not coated present exposed metal surfaces that can corrode in electrolytic or galvanic reactions. Since these components have intricate geometries and/or are required to serve an electromechanical function, they often cannot be completely coated and protected. Other means must be used to protect these components such as correct component placement (away from areas that might trap water), component selection, and the use of plating technologies resistant to corrosion (gold plated contacts, while not totally immune to corrosion, are nevertheless more resistant to corrosion). Wiring and connector design is often one of the more difficult elements of corrosion mitigation.

Quality control of conformal coatings

Many coating systems include UV indicators that can be used for post cure inspection of the encapsulated PCB under a UV inspection lamp (Figure 13). Inspection is typically performed by a trained technician who checks for bubbles, voids, blisters, wrinkles, incomplete wetting, and coverage errors in the final coat. Post inspection is critical to a successful conformal coating operation, as small changes in the manufacturing process can trigger errors that would otherwise go unnoticed.

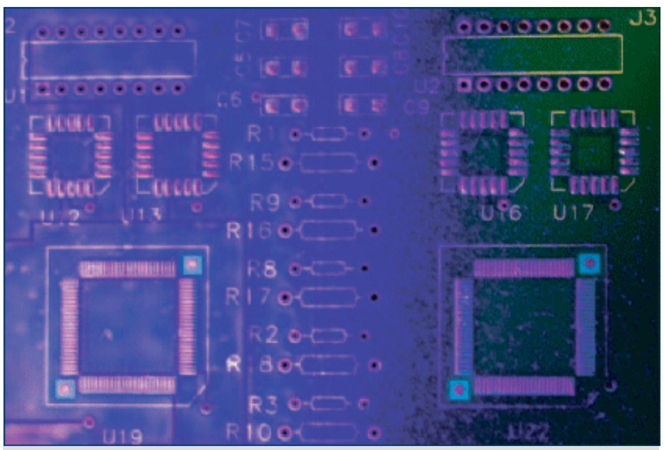

Figure 13. UV inspection reveals uncoated PCB areas

Potting and Encapsulation

Potting an electronic circuit board or device involves filling an enclosure containing the device with a liquid polymer that cures to a hard or soft solid encapsulant. This can provide a very high degree of environmental protection to the potted components.

Encapsulation is similar to potting. A polymer is applied to the protected component that surrounds and encloses sensitive parts. Unlike potting, however, encapsulation does not use or retain an enclosure after the polymer cures. Removable molds are sometimes used, or the encapsulant may have a high enough viscosity that it can hold its shape and position during the cure cycle. Back substrate solar panels are a good example of encapsulation where an uncured polymer is poured over the solar cells on the substrate. The viscosity and surface tension of the polymer keep it from running over the side of the substrate while the polymer cures.

One-part silicone pastes, dispensed from handheld guns or machine automated dispensers, are often used on PCBs to encapsulate connections and to secure larger components like electrolytic capacitors. These formulations must be compatible with the board components and must be non-corrosive. Acetoxy cured silicones will release acetic acid that may corrode copper based metals and must be avoided – alkoxy cured silicones are available that are specifically designed for this purpose and release non-corrosive alcohol vapor as a cure byproduct.

Conformal coating, potting, and encapsulation problems

Problems can arise from improper design and implementation of potting and encapsulation approaches. Many are related to mechanical stress placed on the board by the potting compound. During the cure cycle, care must be taken to avoid excessive swelling and shrinkage of the potting material that could strain the encapsulated components. After curing, differences in thermal expansion can stress component leads or warp the PCB and lead to broken solder joints. The coefficient of thermal expansion (CTE) of the various materials, including potting compound, PCB, and components, must be matched to avoid stress cycles that occur with daily heating and cooling. Epoxy potting compounds tend to be harder and will be more likely to stress the PCB and board components, while silicones as a class are softer and have higher stress relieving qualities in the final assembly.

Problems may also occur when water gets under the encapsulation and/or in between the encapsulation and components. This can result from inadequate adhesion or voids in the cured potting. Wire leads and connectors provide electrical access to the encapsulated components and may also be a path for water ingress under certain design geometry. The edges of encapsulated solar panels and wire junction boxes tend to be points of entry for water and contaminants and are often protected by additional encapsulation and mechanical frame elements.

Conclusions

As product durability increases so too do the requirements for corrosion protection of the component electronics. Corrosion prevention is achieved through proper system design, manufacturing controls, and product testing. Process quality control is essential to preventing PCB contamination and proper adhesion of applied coatings.

In many cases, coatings and encapsulation materials will be used to protect the sensitive electrical circuit elements of a pico-powered lighting product. The success or failure of these coatings involves a number of factors including process quality control, material selection, and specific product design geometry.

No single approach will be appropriate for all product designs. A careful study of the specific materials and geometry of different products will lead to different design decisions and manufacturers are encouraged to explore novel approaches to increase the corrosion resistance of their designs.

References

1. “Corrosion and Protection of Electronic Components in Different Environmental Conditions - An Overview”, Vimala et al, The Open Corrosion Journal, 2009, 2, 105-11
2. “A review of Corrosion and environmental effects on electronics”, R. Ambat, Dept. of Manufacturing and Management, Technical University of Denmark
3. “Preventing Corrosion of PCB Assemblies”, D. Culen, OnBoard Technology, October 2008
4. “Considerations for selecting a printed circuit board surface finish”, R. Schueller PhD, DfR Solutions
5.http://www.empf.org/empfasis/dec04/coat1204.htm
6.http://www.empf.org/empfasis/2009/may09/conformal.html
7. Information on conformal coatings provided by Humiseal (US manufacturer of conformal coatings) www.humiseal.com