Connectors 101: What Lighting Designers Need to Know

Written by: **Ron Weber**
Tyco Electronics
Technical Market Manager, Lighting
717-986-3443
mweber@tycoelectronics.com

Introduction

While pronouncements of the death of incandescent lights are premature, their future is dimming as new technologies offer high efficiencies and lower energy consumption. Solid-state lighting technology, in particular, is quickly entering the lighting mainstream. Arguably the most prominent and nearest term solid-state lighting source suitable for general lighting is the ubiquitous LED, albeit a high-power version. Already the favored technology in such applications as signage, jumbo displays, and emergency lighting, these high-intensity LEDs are also finding use in interior accent and architectural lighting. At some time not too far off, LEDs will replace household incandescent lighting as the technology matures, costs decline, and energy-efficiency mandates are implemented.

Making new lighting technologies more affordable and thereby enabling new applications falls into two main categories:

Semiconductor processing: This category includes issues of both materials and fabrication. While outside the scope of this article, it must be mentioned as a key driver of commercial viability of solid-state lighting technology. As manufacturers solve fundamental materials problems, improve yields, and move to volume production, costs will decline.

Packaging: Packaging the light source for its final application is the area that is directly affected by the lighting designer and can significantly affect long-term reliability, cost, and usability. Where an incandescent light and its fixture are relatively simple embodiments of the well-know Edison socket, LEDs present a whole set of different and more challenging issues. Since these LEDs are essentially point sources of light, new thermal, optical, and packaging/integration considerations come into play. High power densities make thermal management a critical part of the fixture design process. Some level of electronics drive circuitry is required to provide the required constant current source. With few exceptions, LEDs cannot be plugged directly into a normal AC line voltage source.

Connectors and Solid-State Lighting

Our concern here is with connector technology and the ways it can help (or hinder) making lighting more affordable and easier to apply and use. Connectors remain a critical part, but have too often been left to the end of the development cycle. This lack of foresight can result in fewer choices and higher costs (including cost of materials, cost of assembly, and cost of upkeep). Integrating connector selection into early design phases opens options, gives more choice, and often lowers costs.

Not only is it important to consider connectors early in the design to gain the widest array of options, it's equally important to understand some of the basics of connector technology to allow informed decisions about various options and tradeoffs. The connectors shown in Figure 1, for example, are low-profile, surface-mount (SMT), two-position connectors designed for use in PCB-based LED strings, lighting controls, and other applications that can benefit from an easy poke-in wire termination to the

PCB. The connector speeds assembly and routine maintenance of lighting systems through an application-specific design.

Figure 1. Connectors specifically designed for LED applications can lower design and assembly costs.

Connector Basics

For our purposes, the basic connector consists of a housing and contacts used to create a separable electromechanical interface. The interface can be used for wire-to-wire, board-to-board, and wire-to-device/board connections. From a practical perspective, a connector is a system in which all the elements combine to make the connector work in its intended application. As shown in Figure 2, these physical elements can be segregated into:

- Housing design and material
- Contact design and material
- Contact plating system

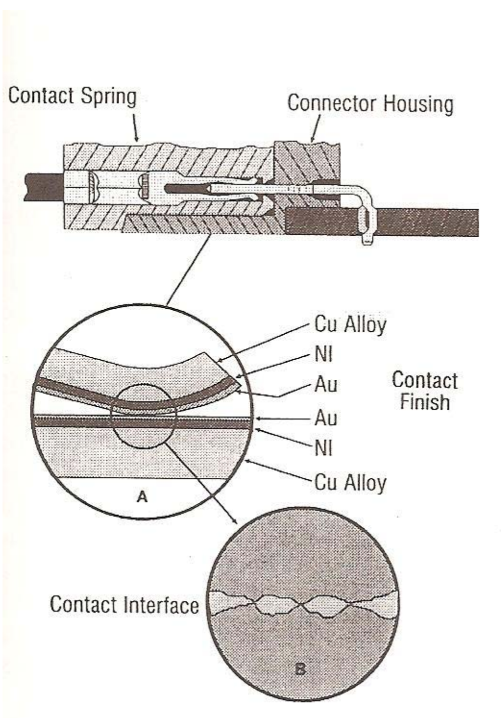

Figure 2. A separable connection includes a housing, contact, and contact plating.

Contact Basics

The purpose of the contact is to establish and maintain a reliable, yet separable low-resistance connection. There are four major characteristics to this:

- Electrical
- Mechanical
- Thermal
- Environmental

Electrically, the contact exerts some manner of spring force to achieve the normal force required to achieve the low resistance. Mechanically, the contact must exert sufficient spring force to maintain normal forces long term. Depending on the application, the spring force must accommodate vibrations and other mechanical disturbances. The interface and bulk contact must be properly sized to stay cool for the rated current it will carry. To keep the interface resistance low, the contact's surface must resist the formation of nonconductive films, corrosion, and other effects.

Spring properties and normal force are mainly a function of the base contact material. Plating over the base material guards against corrosion and other environmental deterioration.

Electrical Concerns

The two most fundamental electrical criteria for any connector system are the voltage and current level.

Traditionally, anything 1 amp or less and under 10°C temperature rise is considered a signal connector. Signal contacts typically have one or two contact interfaces and often incorporate gold plating for the lowest possible interface resistance. Due to tight contact spacings, signal connectors are not well suited to higher voltage applications (typically >48 volts) due to voltage separation requirements so they remain relegated to low-voltage applications. Although signal contacts have an inherent low current rating, higher currents can be carried through these connectors by using multiple contact positions in parallel; however, the manufacturer should be contacted to obtain the appropriate derating factors for the contacts when paralleled. Similarly, higher voltage ratings are sometimes obtained by skip-loading contacts—that is populating every third or fourth contact position to increase the distance between contacts.

Power contacts can be characterized as having current ratings greater than 1 amp and greater than 10°C temperature rise in use. Power connectors are typically larger and have fewer contacts since adequate contact material is needed to carry current without significant joule heating of the contact body. Multiple contact interface points are desirable since they provide parallel paths that serve to minimize interface resistance and decrease joule heating at the interface. Since power contacts usually can handle higher voltages, contacts must be spaced further apart to meet agency dielectric withstand voltage requirements and also provide protection against inadvertent contact.

Contact Materials

The contacts used in a connector system are at the heart of what makes a connector work. Proper material selection for the end application is always challenging as it is a compromise between cost, mechanical performance, electrical performance, and physical size constraints. Correct material selection is critical to be sure adequate normal force is retained at the interface during the life of the connector.

Most contacts use a copper alloy. Brass, an alloy of copper and zinc, is arguably the most common material, finding use in appliance, consumer, HVAC, lighting, personal computing, and other similar applications. Brass contacts can be found in both medium pitch signal and power contact applications. Brass is a good balance between cost, conductivity (set forth as a percentage of International Annealed Copper Standard, which expresses the conductivity of an alloy as a percentage of the conductivity of pure annealed copper), and mechanical performance. It is readily available in various strengths that allow it to be used in a wide variety of applications. It does have some environmental corrosion issues, particularly with respect to ammonia that attacks brass vigorously, so some sort of plating system is strongly recommended when the end use is in such environments.

Also heavily used for connector contacts is phosphor bronze, which maintains excellent long-term spring properties (without stress relaxation) and can handle higher continuous use temperatures than brass. With better spring properties than brass, phosphor bronze lends itself to smaller contacts where the enhanced spring properties can best be leveraged. A broad range of general and proprietary alloys based on phosphor bronze provide an equally broad range of conductivities and mechanical properties that are used throughout the connector industry. Phosphor bronze contacts are usually found in small and medium-pitch signal and moderate-power connectors.

The last most commonly used copper alloy is beryllium copper. Beryllium copper is considered a premium material and is used where the superior spring properties are put to best use in minimizing contact size and, in applications such as aerospace or military, weight. It is significantly more expensive than the brass and phosphor bronze but has an added benefit that it can be readily heat treated to further enhance spring properties. Applications for beryllium copper are usually found in small, fine pitch telecom-type connectors.

Other contact materials or configurations such as semi-exotic copper alloys also exist that are a combination of various elements. Monolithic examples of these alloys are copper-iron (CuFe) or copper-nickel-silicon (CuNiSi) alloys that provide excellent performance in those applications that can benefit from such a premium contact material. Clad materials consisting of one material bonded on top of another are also available but are used in the rarest of instances due to their cost. Another unique contact material configuration occasionally seen takes advantage of the high conductivity of electrolytic tough pitch (ETP) copper, combined with a separate spring member made of stainless or plated steel to provide the required normal force. In many high-temperature applications, such as electric oven burner elements, steel or steel alloys may be used, although conductivity is drastically reduced compared to that of copper alloys. The use of ferrous contact materials requires careful design consideration by both the connector designer as well as the designer of the product that it is used in. Inherent corrosion issues require that steel contacts must be durably and robustly plated.

Contact Platings

Platings can be broadly categorized into two groups: noble and non-noble materials.

Noble platings are characterized exclusively by the pure gold or gold alloy used as the final plating in the system. By their nature, gold plating systems reign supreme for signal applications since noble materials do not corrode or oxidize and, therefore, maintain very low resistance interfaces. Pure gold, being very soft, is seldom used alone and is typically alloyed with cobalt or palladium to increase the hardness of the surface. Contact interface normal forces can be very light with gold (50 grams or less) making it very desirable for high-pin count connector systems, where the combined mating and unmating forces can be quite significant.

Since gold plating is costly, gold plating on contacts is very thin and, in a number of instances, very selectively placed on the contact interface. Figure 3 shows some strategies in plating. As gold prices escalated, plating the entire contact (a) became prohibitive. Selective plating (b), where gold is applied only in the areas where it will benefit the electrical performance, is increasingly common. Another approach is dual plating (c), where gold is applied at the separable interface and tin is used for permanent soldered or press fit connections, further reducing the use of gold without decreasing performance.

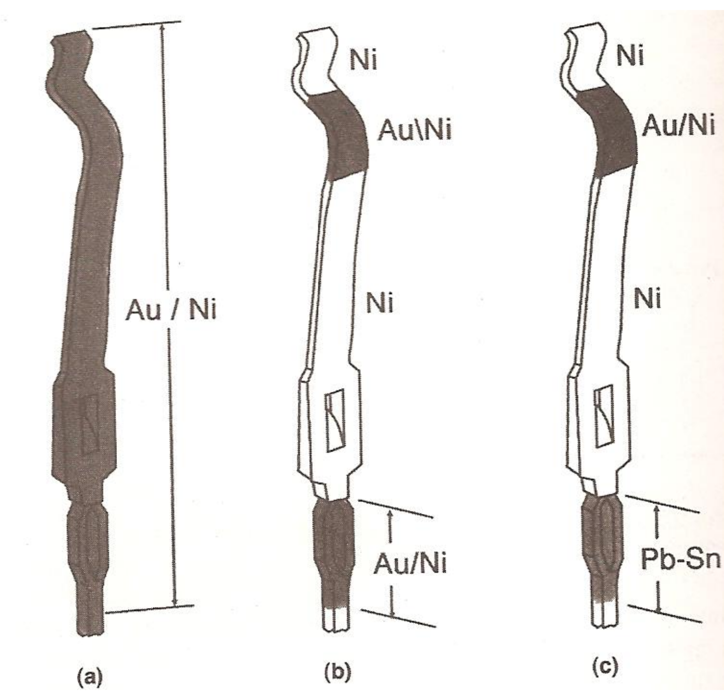

Figure 3. Approaches to plating to reduce gold without decreasing performance.

Gold plating is almost always applied over some type of barrier plating, most often nickel, to minimize pore corrosion (Figure 4). While the gold itself does not corrode, pore corrosion results from microscopic pores that occur in the gold at thin plating thicknesses. These pores, when they extend to the base contact material, can form corrosion products on the surface of the plating. However, when a nickel underplate is used, the nickel is exposed in these pores and we can take advantage of the inherent self-passivation properties of nickel to limit corrosion products from forming. Without the nickel barrier, corrosion will inevitably form and degrade the contact interface. Experienced connector suppliers with a long background in contact physics have finely tuned plating systems and coatings that mitigate the effects of pore corrosion.

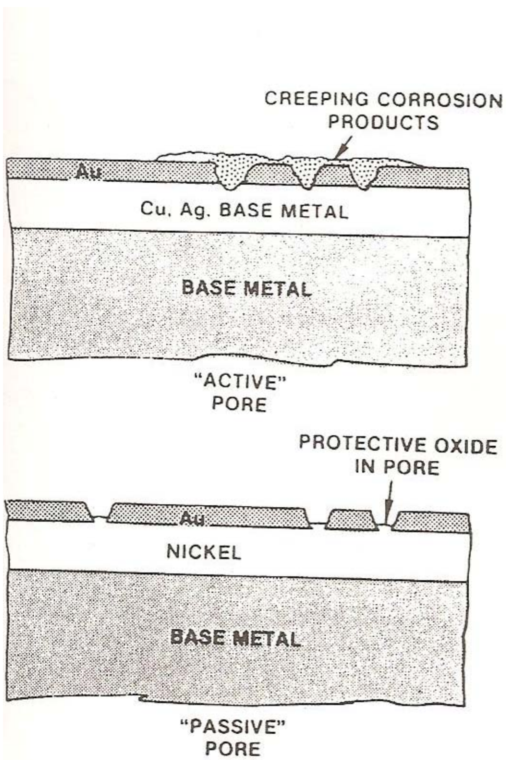

Figure 4. Nickel prevents corrosion from migrating through micropores from the base material through gold plating to the surface.

As one might expect, non-noble platings—typically tin, nickel, and silver— are subject to corrosion. Tin and tin alloys dominate as non-noble contact platings. When a connector is correctly designed and the appropriate environmental considerations are made, tin plating systems can form a very durable and cost-effective interface for most applications.

Non-noble platings are typically applied in a thicker layer to ensure adequate barrier properties and require higher normal forces to break through the inevitable non-conductive oxides that will form on the surface. The exception to this is silver-based platings where the oxides are relatively soft, malleable, easily displaced, and conductive. There are various anti-oxide coatings that can be applied to minimize the formation of these oxides, but they cannot be eliminated altogether, so mitigating the effects of these oxides falls to the experience of the connector designer.

So what happens when oxides form on non-noble platings? The biggest degradation mechanism affecting tin and, to a much lesser extent, silver is fretting corrosion. Fretting corrosion occurs through micro-motions on the contact interface and can be thermally or mechanically induced. Where these micro-motions cause problems is in oxide formation.

To use a medical analogy that all of us are familiar with, when a micro-motion induced movement occurs, it opens a fresh “wound” in the plating surface. As expected, the wound eventually “scabs” over with a non-conductive oxide layer. As shown in Figure 5, the problem occurs when a micro-motion induced movement moves the contact interface back over the oxide “scab.” The contact normal force partially re-opens the scab so the interface becomes a higher resistance mix of oxide and metal contact areas. In the meantime, the area that the interface just moved from also forms an oxide “scab.” Micro-motion again moves the contact on top of this oxide layer. With each successive micro-motion, the oxide “scab” layer builds while the conductive metal contact areas diminish resulting in increasing interface resistance.

In a signal application, the resistance eventually builds to the point where the connector no longer conducts the signal. In a power/current-carrying application, the results are much more dramatic since increased interface resistance results in increased joule heating of the interface and contact. The increased heating of the contact eventually builds to the point where it anneals the contact material and gradually reduces the normal force exerted at the interface. With decreasing normal force comes increased resistance that further increases the heating at the interface. Eventually, this vicious heating cycle will cause the interface to catastrophically fail. Mature connector suppliers are well aware of this phenomenon and take steps in their manufacturing and plating processes to minimize the fretting corrosion that leads to this failure mechanism.

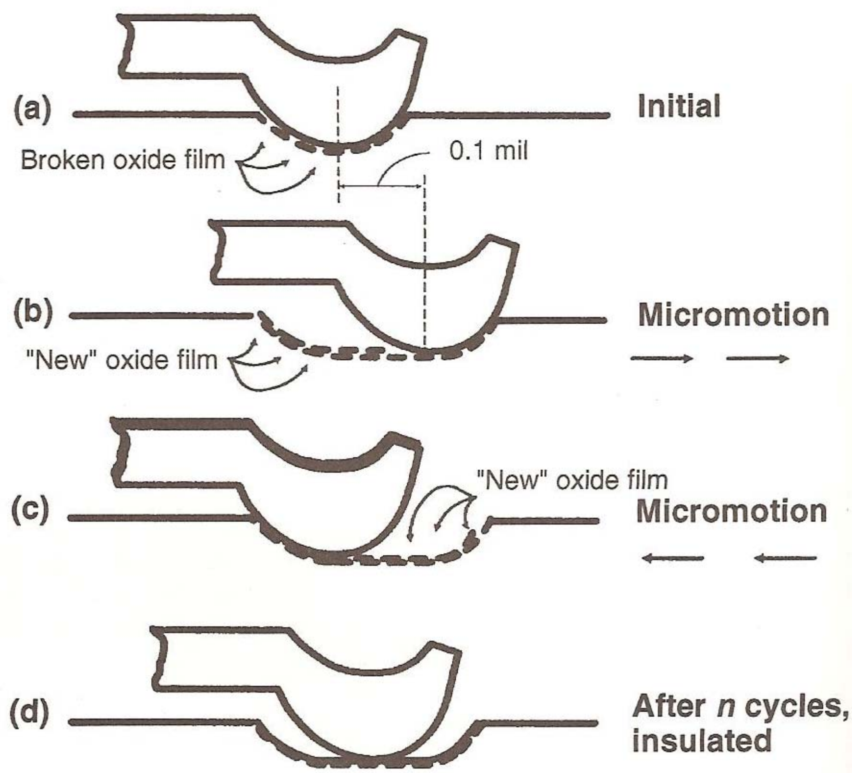

Figure 5. Fretting corrosion from micromotions

Mating Gold to Tin

So, what about mating a tin-plated connector to a gold-plated connector? One could reason that you'd get the benefits of both systems. In this case, that reasoning would be wrong. In reality, what happens is some of the tin actually transfers to the surface of the gold during the initial mating. This transferred tin forms the nucleus for tin oxide growth on the gold plating. In the end, you still end up with the same fretting corrosion possibility with a mixed plating system even though you paid a premium for the gold-plated half of the connector system.

All is not gloom and doom with non-noble platings. A properly designed connector system mitigates the formation of these oxides, primarily by providing an initial wiping motion on mating to break through films and the use of a minimum 100 grams of normal force to minimize micromotions. The use of contact lubricants and anti-oxide compounds in the manufacturing process further prevents the fretting corrosion from occurring thereby providing a stable long-term interface. The experience and technical expertise of the connector designer and manufacturer determines how well the connector performs in the end. The "Tin Commandments" developed by Jim Whitley at AMP Incorporated (now Tyco Electronics Corporation) over a half century ago still ring true today:

1. Tin-coated contacts should be mechanically stable in the mated condition
2. Tin-coated contacts need at least 100 grams contact normal force
3. Tin-coated contacts need lubrication

4. Tin coating is not recommended for continuous service at high temperatures
5. The choice of plated, reflowed, hot air leveled, or hot tin dipped coatings does not strongly affect the electrical performance of tin or tin alloy coated contacts
6. Electroplated tin coatings should be at least 100 microinches thick
7. Mating tin-coated contacts to gold-coated contacts is not recommended
8. Sliding or wiping action during contact engagement is recommended with tin-coated contacts
9. Tin-coated contacts should not be used to make or break current
10. Tin-coated contacts can be used under dry circuit or low level conditions

Housings

The connector housing provides a number of very important functions. Fundamentally, the housing provides electrical insulation between adjacent contacts and between the contact and the outside world. This insulation is usually verified and stated as a voltage in the Dielectric Withstand Voltage (DWV) rating for the connector. A properly designed housing further holds the contacts in one half of a connector in correct relationship with the contacts in the mating half to provide trouble-free mating and unmating. The housing also fixes the spacing between contacts and defines the creep (electrical tracking distance over surfaces) and clearance (linear “line-of-sight” distance) between contacts. In some instances, the housing provides different cavity configurations to allow a mix of signal and power contacts. In yet other applications, connector housings are integrated with a larger circuit enclosure providing an added value to the customer. Lastly, the housing provides some level of environmental protection to the electrical contacts.

Environmental Concerns

The environmental protection provided by the housing can encompass preventing contaminates (both solid and liquid) from getting into the connector interface and also preventing inadvertent physical contact with the electrical contacts. To prevent interface contamination, various sealing techniques are used. In sealed connectors, the housing, in conjunction with various sealing devices, serves to prevent contaminants from entering into the contact area. Electrical connector housing sealing levels typically adhere to the well-recognized IP levels (Figure 6). EN 60529 outlines an international classification system for the sealing effectiveness against both objects (tools, dust, fingers) and moisture. This classification system uses the letters IP (for *Ingress Protection*) followed by two digits. The first digit refers to protection from physical objects; the second digit deals with moisture. Most unsealed connector systems, therefore, have an inherent IP20 rating.

Number	**Protection Against**	
	1st Digit	**2nd Digit**
0	No special protection	No special protection
1	Objects greater than 50 mm in diameter; hands and other large body parts	Dripping water
2	Objects greater than 12.5 mm in diameter; fingers	Vertically dripping water
3	Objects greater than 2.5 mm in diameter	Sprayed water
4	Objects greater than 1.0 mm in diameter	Splashed water

5	Dust sufficient to interfere with operation of the equipment	Water projected from a nozzle
6	All dust (dust tight)	Heavy seas or powerful jets of water
7		Immersion
8		Complete, continuous submersion in water

Figure 6. IP sealing levels

Preventing physical contact with the electrical contacts is also a key function performed by the housing and is particularly important in higher voltage applications. At a minimum, having some housing protection prevents or at least minimizes potential handling damage to the contacts themselves that may occur during assembly or installation of the end product. When dealing with elevated voltages (usually above 48 volts), most safety standards require design features to prevent accidental physical contact with the electrical contact. In this case, contacts are recessed to some extent and often shrouded as a mechanical barrier to contact. Most standards around the globe use a “standard” probe to confirm housing design is adequate to prevent access.

Lastly, the housing must be robust enough to handle the end application’s environmental conditions. It is important to understand and establish what these are early in the selection process. If outdoor use is anticipated, then it is natural to specify a housing with a UV exposure rating. If a connector is expected to be used in an abusive environment where it is subject to mechanical shock and impacts (such as what would be used in a concert or stage setting), then perhaps a heavily impact modified polymer housing would be used or, perhaps even a connector with a protective metal shell. High- or low-temperature applications require particular housing materials and determine whether thermoset or thermoplastic materials need to be used. If active latching is required, the designer must specify a polymer material that allows latch flexibility while still meeting other mechanical and electrical requirements. Even chemical exposure needs to be considered, for example, if the connector is to be used in gasoline pump applications, you need to make sure the housing material can withstand continued exposure to volatile hydrocarbons without becoming brittle or fracturing.

Connector Ratings

In selecting the best connector for an application, basic electrical, mechanical, and environmental performance requirements must identified and considered to optimize the selection.

Electrically, the connector must be compatible with the current levels and voltages of the application. Certainly, the basic continuous voltage and current needs to be considered but, in addition, transient and surge conditions that may occur over the life of the product need to be identified.

Mechanical considerations can cover a broad range of features. As with all electronics, the trend is toward miniaturization, so connectors require tighter contact pitches to pack more contacts in a smaller area. As a result, the physical size of the connector relative to the application needs to be considered in selecting the connector. Mating direction and wire dress similarly need to be considered relative to their intended application in the system. How the connectors are held together after mating can also impact the selection process since some connectors rely on active mechanical latches, others utilize small detent bumps, and some have nothing other than friction to hold them together. Beyond obvious form factor issues, the connector must also be evaluated for the degree in which it can withstand mechanical abuse, such as vibration, shock, and the like.

Environmentally, the connector must withstand both application temperature ranges and processing temperatures (such as those experienced during reflow soldering of surface-mount connectors). The application environment will define additional needs, such as sealing, ability to withstand solvents or salt spray, high altitudes, or other extremes. In outdoor application, UV exposure capability is critical to reliable, long term connector performance.

While typically not seen in lighting applications, shielding in a noisy electromagnetic environment may also be necessary. In some instances, both shielded and unshielded versions of the same connector are offered by connector suppliers. The connector must be designed specifically to terminate the cable's shield since it is practically impossible to convert a non-shielded connector design to a shielded one. The key to a reliable, effective shield is to provide a 360° termination that maintains a low-impedance path from the cable through the connector to ground.

Thermal Considerations

Signal applications typically do not require thermal management. Power applications do. Power contacts have a current rating that indicates the maximum current that the contact can continuously carry. This rating is usually based on a 30°C temperature rise on the contact and is based on measurements of a single contact. When multiple power contacts are used in a housing, the allowable current is derated to allow suitable heat dissipation. It is important therefore for the end user to consult the connector's product specification to determine the suitable current de-rating factor when evaluating a connector system.

In high-intensity LED applications, the LEDs themselves generate enough heat to require careful consideration to thermal management—typically this is accomplished by a heat sink and sometimes forced air cooling. The challenge of integrating thermal management into a system is an excellent example of why it is important to consider interconnections early in the design process. This often poses unique system packaging challenges since most of the new high-intensity LEDs are small and are often packaged as surface-mount devices (SMD). Integrating the connector system in amongst the LEDs, circuit boards, optics and thermal devices is often quite challenging if left to the end of the design process. Evaluation of the interconnect earlier on in the design process provides for a more tightly integrated, optimized solution that can make assembly and, if needed, repair much more efficient.

Beyond the normal electromechanical aspects, new interconnections must also address the special needs of solid-state lighting. These include higher operating temperatures and the ability to provide housings in specific colors so the connector blends into the visible parts of the lighting designer's fixture. Further, for lighting applications, it is often very desirable to use circuit board-mounted connectors with softened edges to minimize shadowing and the possibility of partially occluding the light output of the low profile surface mount LEDs.

The Next Step in Connectors

So now that we've defined the key elements of a connector, let's expand the definition a bit. From an application standpoint, it is well known that LEDs perform better when operating at lower temperatures. As mentioned earlier, current LED lighting design methodology usually incorporates one or more LEDs onto a circuit board, usually metal clad for thermal reasons. This assembly is then integrated into the fixture by a lighting fixture designer. Throwing out conventional logic that mandates a circuit board in the system, one could combine a heat sink into the electro-mechanical design of the connector to create a thermo-electric connector that mates directly to the LED.

An example is the high-intensity LED holder (shown in Figure 7) that Tyco Electronics designed for use with a high-intensity LED. The holder combines a small footprint and low profile with a snap-together contact system for both direct electrical and thermal connections directly to the LED. Without the need for solder, thermal adhesives, or metal-clad printed circuit boards, application is simple, cost effective and expands mounting options beyond the planar constraints of circuit boards. As an added benefit, replacement of a faulty LED or changing colors is equally straightforward since all it entails is removing the retention clip, removing the LED, and replacing it with a new one. The basic holder kit includes a contact carrier and an LED retention clip used to secure the LED to the carrier. The module-to-cable interface is a standard two-position Tyco Electronics' Mini CT post and receptacle connection that facilitates plug-n-play operation.

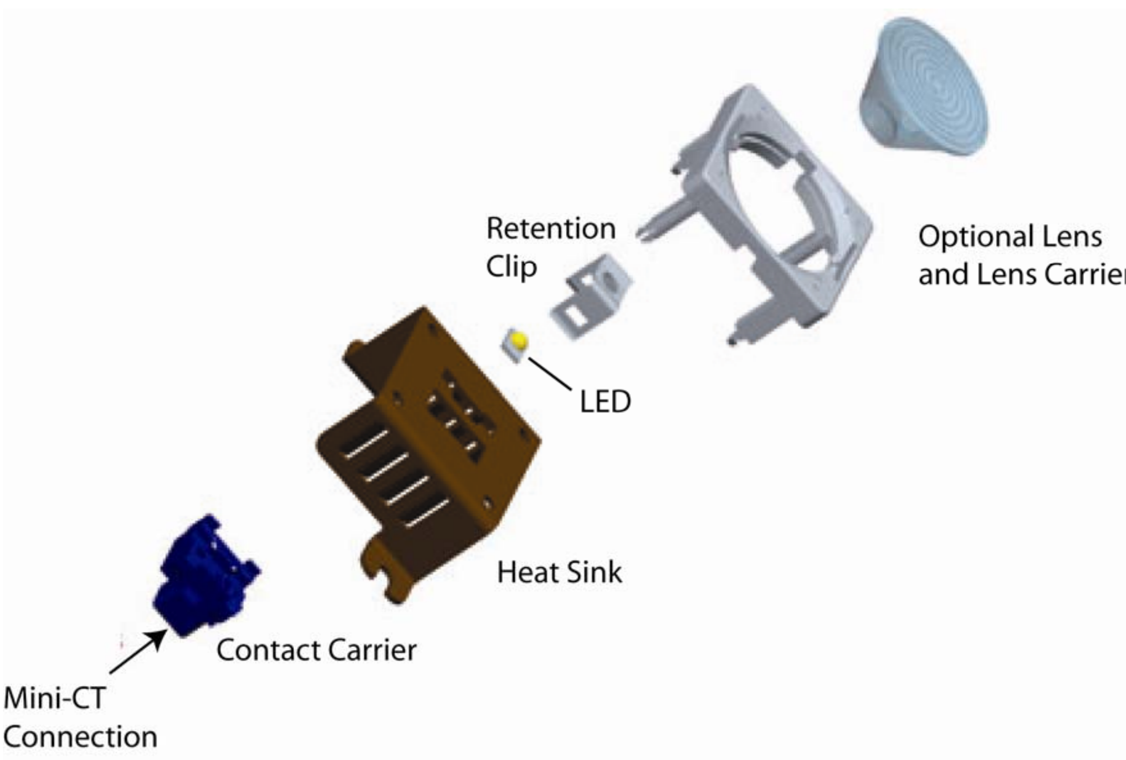

Figure 7. High-intensity LED holder comgines thermal, mechanical, and electrical management into a single, easy-to-use system.

A Note on Standards and Approvals

Naturally, any connector must meet agency requirements for any region of the world in which it is used. Regulatory agencies like UL and CSA in North America and IEC, TUV, and VDE in Europe have requirements to provide for safe application of a product. Selecting components that have already gone through the approval process speeds design and simplifies approval of the final product. Given the global nature of the lighting market, the designer must confirm components meet all regional or local requirements. Being cognizant of the connector agency requirements as well as those needed by the end application is critical to the successful selection and integration of the appropriate connector system.

A Quick Checklist

The following list gives an overview of the myriad of decisions involved in selecting a connector. It is often very beneficial to consult the product specifications (that define connector performance) as well as application specifications (that define how to use the connector) to confirm the connector meets the intended end application requirements. This checklist can serve as a valuable guide when you discuss the connector requirements with your preferred connector supplier.

- ✓ **Agency requirements**
  - ✓ UL (e.g., UL 1977 often applicable for connectors)?
  - ✓ CSA?
  - ✓ VDE/TUV?
  - ✓ Other?
- ✓ **Performance requirements**
  - ✓ Current?
  - ✓ Voltage?
  - ✓ Number of positions? Specific centerline?
  - ✓ Connector envelope size requirements (height, width, length)?
  - ✓ Wire gauge size, type, and range?
  - ✓ Hot plugging – capacitive or inductive load?
  - ✓ Mating/unmating force desired?
  - ✓ Mating direction, vertical or right angle?
  - ✓ Make-first ground required?
  - ✓ Maximum/minimum temperature (both operating and processing)?
  - ✓ Chemical/solvent resistance?
  - ✓ Durability, mating cycles?
  - ✓ Shock & vibration requirements?
  - ✓ Sealing level required. To what IP level?
  - ✓ Wire/cable/PCB retention requirements?
  - ✓ Footprint compatibility required?
  - ✓ PCB mounting: SMT or through-hole, right angle or vertical header? PCB thickness?
  - ✓ Customer-specific performance/test requirements?
  - ✓ What product variations *might* be required?
    - ✓ Color?
    - ✓ Height/width/length?
    - ✓ Select contact loading?

Conclusion

Selecting the best connector for a lighting application is a matter of matching application requirements to available connectors, with proper consideration given to performance and costs. We can't stress enough the wisdom of giving connector selection the same thought and consideration as you give thermal, optical, and electrical issues at the early design stage. Indeed, the right connector can address these issues.

We haven't mentioned cost. The acquisition cost of the connector is one thing. The applied cost is quite another. Newer generations of application-specific connectors for lighting can reduce engineering costs, manufacturing costs, warranty costs, and maintenance costs. But one key to realizing these savings is to understand connector basics and to integrate connector selection into the overall design process.

These new solid-state lighting systems with their inherent longevity demand equally robust connector systems while the LEDs, thermal solution, optics, and packaging comprise a considerable part of the overall cost of the lighting system. The connector is usually a small part of the overall cost and is often specified without adequate consideration and balancing of cost versus performance. It makes little sense to scrimp on the one component that your entire fixture relies on for power. Without a reliable and appropriate connector system, the lighting fixture, however well designed and esthetically pleasing it is, becomes a dull, static (and unlit) non-functional object d'art. Spend some time and consideration selecting the appropriate proven connector system for the application even if it costs a little more. It will pay dividends in the long run.

Tyco Electronics
Our commitment. Your advantage.