LUXEON Illumination LEDs

Circuit Design and Layout Practices
to Minimize Electrical Stress

Introduction

LED circuits operating in the real world can be subjected to various abnormal electrical overstress situations. Among the most common are:

- Isolation test during validation or production of the luminaire ("hi-pot test")
- Lightning strikes and line transients
- Hot-swapping of LED circuits (disconnecting and reconnecting an LED circuit board to the driver while the driver remains powered up)
- Driver failures
- ESD (Electro-Static Discharge)

Scope

This paper presents background information on some of these overstress modes and discusses recommendations to minimize the potentially destructive effects of electrical overstress on LEDs.

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1. Electrical Overstress

Electrical Overstress (EOS) can present itself to an LED array in two forms, either as excess voltage or excess current.

Because voltage and current are interrelated, it is not always possible to identify whether a high voltage or high current caused a failure.

Currents can flow through an LED array in two ways: differential mode and common mode (see Figure 1). Differential mode currents can be very destructive. However, a well-designed LED driver from a reputable vendor has built-in controls and protection to eliminate any differential mode fault currents. Common mode currents are more insidious, as they are largely dependent on the circuit board layout, materials used, line surge protection devices etc. Most of the recommendations in this paper are geared towards minimizing the potential for common mode fault currents.

2. Isolation Test Requirements

Isolation tests are required for all electrical appliances that are connected to an AC power line, including luminaires.

A typical luminaire includes LEDs, circuit board(s), heat sinks and other thermal management devices, reflectors/lenses/diffusers, and a power supply.

Which components are included in the isolation test depends on where the mains separation is implemented in the system. Specifically, the electrical connection from the components being tested to ground is critical. The key components addressed are the power supply and the LED board.

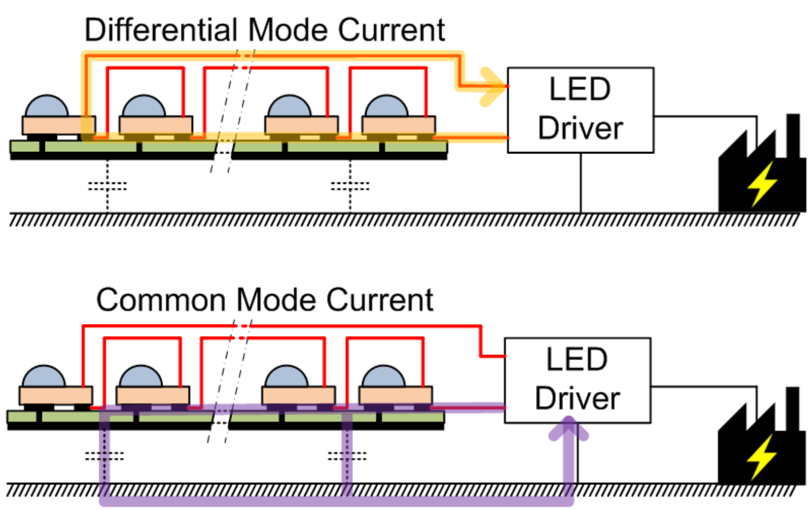


Figure 1. Differential mode (top) and common mode (bottom) currents.

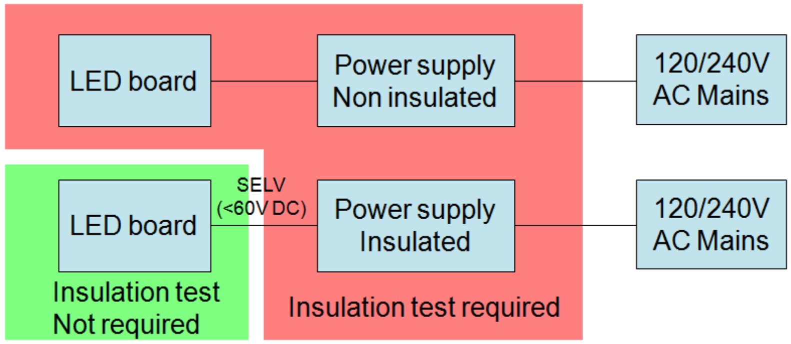


Figure 2. Isolation test requirements.

When an isolated power supply is used and the output is SELV (safety extra-low voltage, i.e. < 60V DC), isolation testing of the LED board is not necessary (see Figure 2). Depending on local regulations, isolation tests may be carried out as design verification or during the production process.

Some important test specifications that should be considered are:

- IEC/EN 60598, Electric Strength or Insulation Resistance Test; test voltage 1.5 kV AC
  - Isolation test between circuitry and ground
  - 1000 + 2 x (maximum working voltage) [V_{rms}] for 1 minute
  - SELV (60 to 120V DC) circuitry needs 500[V_{rms}] for 1 minute test
  - SELV (< 60V DC) does not need test
- UL 1598: Electrical Safety for Luminaires

3. Isolation Test on an LED Board

An isolation test checks the safety isolation between the power supply line and the case ground in order to protect users from electric shock. The test method used depends on how the electrical connection between the circuit board, power supply and heat sink is constructed. Figure 3 shows an example of a typical luminaire architecture. The metal in the metal core printed circuit board (MCPCB) is usually electrically connected to the case ground through the heat sink. In this case, a high voltage AC source is applied between the copper traces on the MCPCB and the metal carrier, thereby testing the MCPCB's dielectric layer. When additional isolating materials are used between MCPCB and heat sink, the high voltage is applied to the heat sink and the board traces in order to test the MCPCB's dielectric layer and additional isolating material in series. During the test, all terminals connecting to the board are on one side of the high voltage AC source, while the other side of the AC source is connected to the case ground.

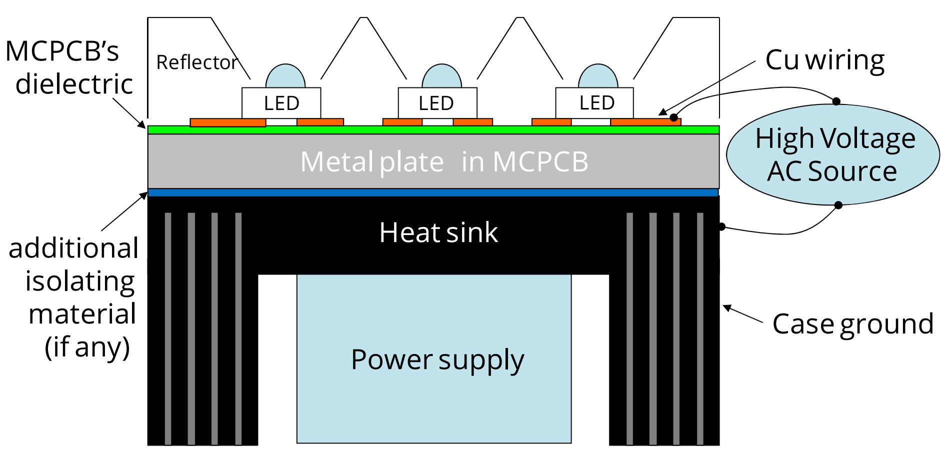


Figure 3. Isolation test of LED board - typical setup.

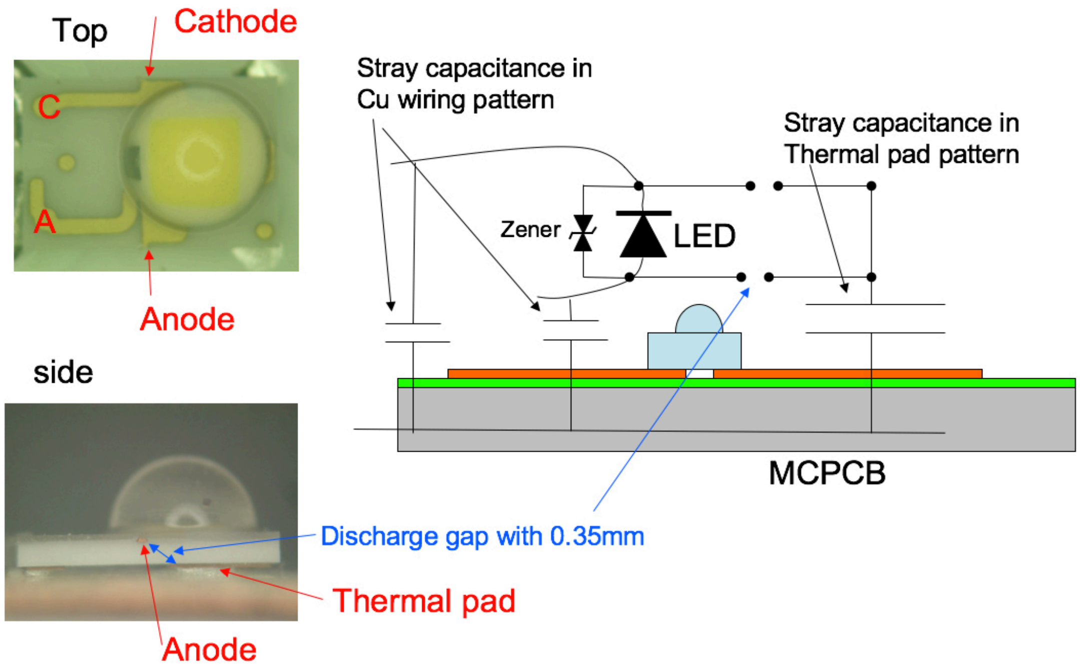


Figure 4. Equivalent electrical circuit model of a LUXEON Rebel LED on a PCB.

4. LUXEON Rebel LED Circuit Model on a Board

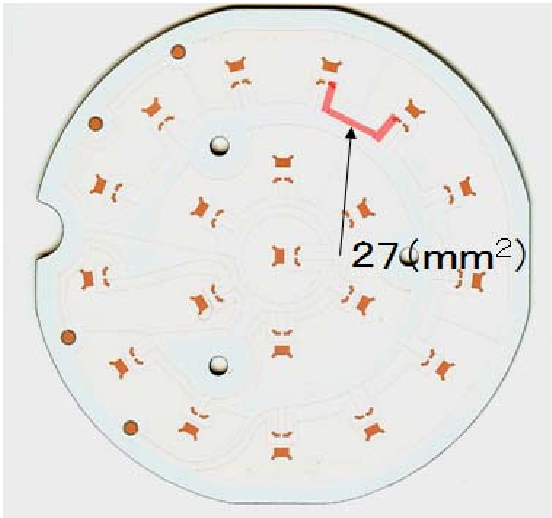
Since the equipment, which is used to perform isolation testing, is very specialized and expensive, it is common to use circuit simulations during the design phase to predict stresses. Figure 4 shows the equivalent electrical circuit of a LUXEON Rebel LED on a MCPCB. This circuit includes the LED, the transient voltage suppressor (TVS) within the LED package, board trace parasitic capacitance, thermal pad parasitic capacitance and arc gaps ("discharge gaps") that represent the short distance between anode/cathode and the LED's thermal pad.

These five elements can be modeled in SPICE 1. For the trace parasitic capacitance, we use the standard capacitor equation, using trace area and the thickness and dielectric constant of the MCPCB dielectric:

$$C = \varepsilon \frac{S}{d}$$

In this equation, C is the capacitance (in F), e the dielectric constant (in F/m), S the area (in m^2), and d the isolation thickness (in m).

[1] SPICE (Simulation Program with Integrated Circuit Emphasis) is a general-purpose analog circuit simulation program. An LED SPICE model provides a compact description of the typical relationship between the drive current I_f and the forward voltage V_f of an LED.



$S : 27\ [mm^2]$

$\varepsilon : \varepsilon_r \times \varepsilon_0$

$= 4.9 \times (8.85 \times 10^{-12})\ [F/m]$

$d : 1 \times 10^{-4}\ [m]$

$$C = \varepsilon \frac{S}{d}$$

$$= 12pF$$

Figure 5. Stray capacitance of Cu wiring on an LED board.

Figure 5 shows an example of an MCPCB for an LED application. The traces shown in red have a total area of $27mm^2$. The thickness of the dielectric layer on the MCPCB is 100µm and its relative permittivity is 3.4. In this case the parasitic capacitance of the trace is approximately 12pF.

The parasitic capacitance of the metal traces connected to the thermal pad of the LED can be estimated in a similar fashion (around 100pF for a LUXEON Rebel thermal pad).

The shortest-path distance between anode/cathode and thermal pad on a LUXEON Rebel LES is 0.35mm. This arc-gap is located on the side of the ceramic substrate (Figure 4). In the high voltage test, this minimum gap may show electrical discharge, either through creepage or arcing. Before simulation, the voltage between thermal pad and anode/cathode has to be verified. If the voltage is less than 35V, arcing or creepage is not likely and the arc gaps can be omitted from the equivalent electrical circuit model of the LED. Note that during the life of the LED application, dirt, moisture and other material may accumulate on the LED, reducing the dielectric strength of this arc-gap; this possibility should be considered in the design phase.

A TVS is incorporated in the LED as a means of ESD protection. This TVS has a zener voltage of approximately 8V. The TVS within the LUXEON Rebel LED was omitted in all SPICE simulations in order to better evaluate the potential electrical stress on the LED itself.

5. Electrical Stress Simulation during Isolation Test

Figure 6 shows the full circuit model of 6 LUXEON Rebel LEDs in series on a board during isolation test. Each LED has its own parasitic capacitance of wiring traces and thermal pad. In this simulation, the high AC voltage is applied between the metal base plate of the MCPCB and the anode/cathode connections.

During the isolation test, AC current flows from the LED array to the case ground through the parasitic capacitances. The leakage current in C1, C2 and C3 is mostly carried by D1, while D2 only carries the leakage current through C2 and C3, and so on. As a result, the LEDs at the end of the string (D1 and D6) carry the highest leakage currents during the test. With a larger number of LEDs in a series string, the current through the end LEDs also increases.

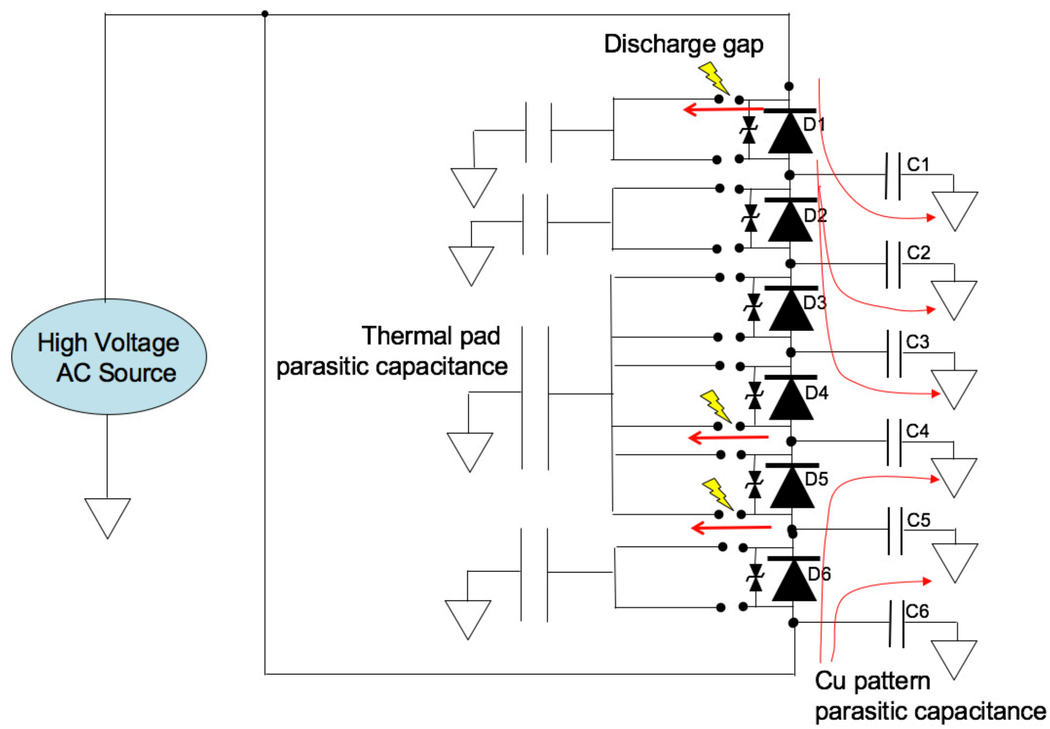


Figure 6. Full circuit model of isolation test.

Figure 7 shows the typical LED voltage for two boards with different LED string counts. In both examples, the parasitic capacitance per LED is assumed to be 12pF and a 50Hz 1000Vrms AC source is applied. The LED voltages are the highest on both ends of the LED string. For the string with 6 LEDs in series, the maximum negative voltage is approximately -8V for LED#1 and LED#6. For the string with 12 LEDs in series, the maximum negative voltage is approximately -20V at the first and last LED. This example confirms that the maximum LED voltage increases as the LED count in the string increases.

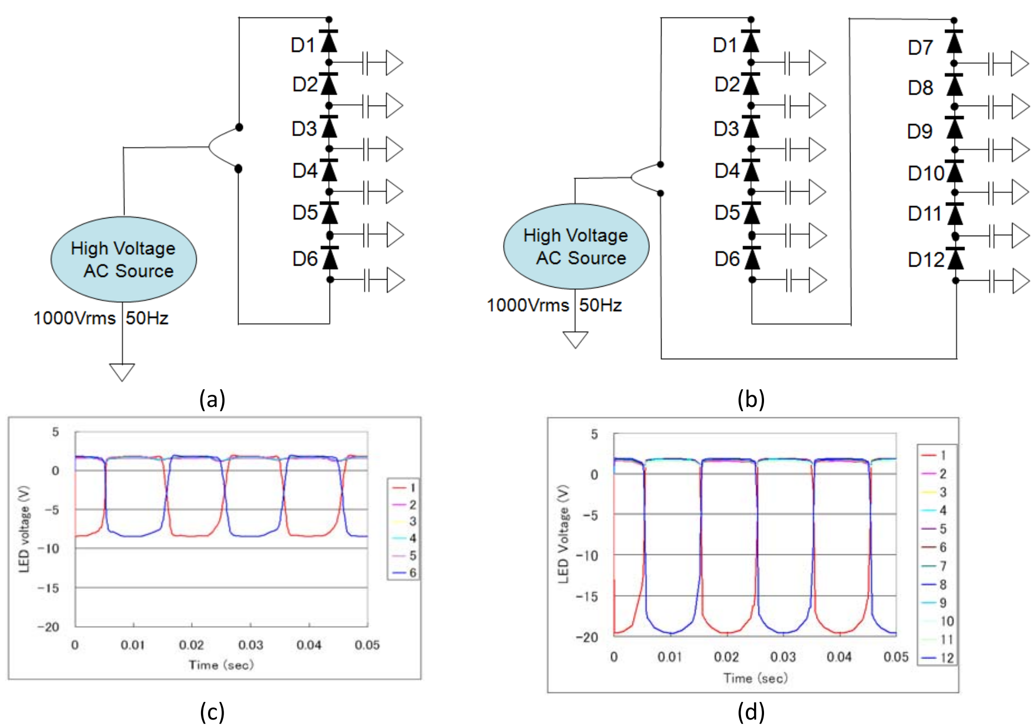


Figure 7. Panels (a) and (b) show representative circuit models for MCPCBs with 6 and 12 LEDs, respectively. Corresponding LED voltage simulations are shown in panels (c) and (d).

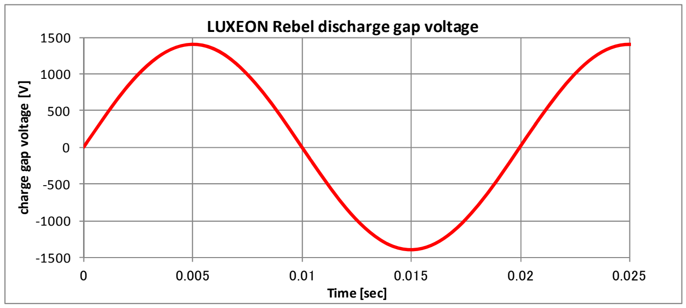


Figure 8. Discharge gap voltage.

Figure 8 shows the voltage across the arc-gap, as simulated in SPICE. In this simulation, only the voltage is calculated; no actual discharge is simulated. Such discharges induce large currents, which will flow through the parasitic capacitances. As a result, discharge will induce excess current or negative voltage stress on the LEDs. This simulation indicates that EOS can be induced in the isolation test, leading to possible LED failure. For this reason, LEDs have to be protected against these voltages.

6. Protection Circuits

Capacitors can be used as protection devices to reduce harmful voltages across the LEDs and to reduce the likelihood of any discharge during the insulation test. Examples of protection circuits are shown in Figure 9. The capacitors in these circuits connect each electrode of the LED with the anode or cathode of the LED string in order to reduce the maximum voltage during AC operation. These extra capacitors, which should be mounted on the PCB, as close as possible to the LEDs, do not affect the board during normal DC operation, but may cause some losses during pulsed operation such as pulse-width modulation (PWM).

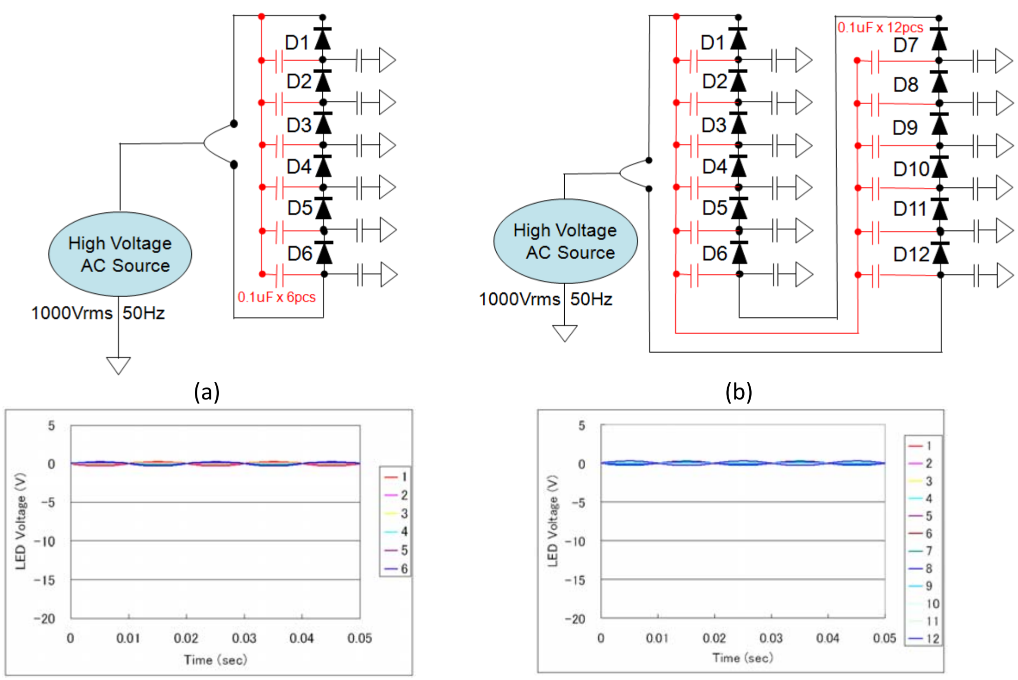


Figure 9. Panels (a) and (b) show representative circuit models for boards with 6 and 12 LEDs, respectively. Both circuits include protection capacitors (in red). Corresponding LED voltage simulations are shown in panels (c) and (d).

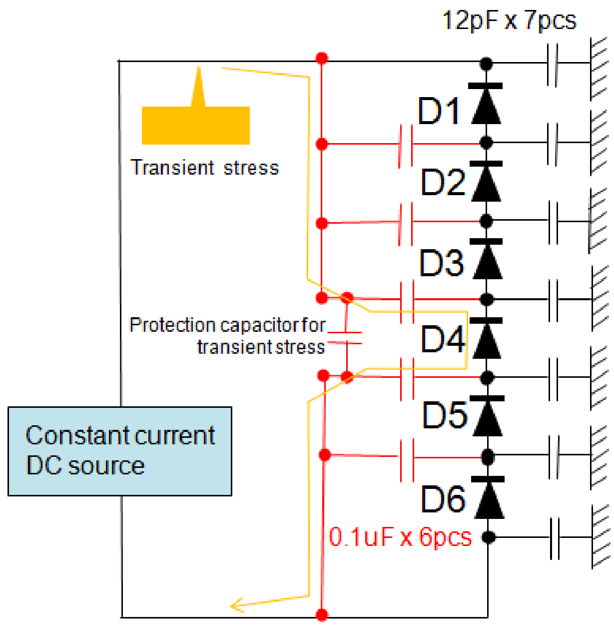


Figure 10. Protection capacitors during normal operation.

The remainder of this section provides guidelines on how to select and dimension the electronic components in this circuit. Note that any dimensions or ratings which are mentioned in this application brief for electronic components are for reference only. Any parameters such as impact on driver, energy build-up, rating of components, component lifetime and so on, depend on the actual application conditions. Lumileds recommends that customers do their own due diligence to ensure all relevant performance and safety specifications are met for the application of interest.

A capacitance of 0.1μF should be sufficient when using 6 or 12 LEDs in series, assuming the total parasitic capacitance per LED is approximately 12pF. Figure 9(c) and Figure 9(d) show SPICE simulation results for the 6 and 12 LED board configurations with protection capacitors. The negative LED voltages on the first and last LED in the string are now reduced to less than -100mV.

It is important to point out that that the selection of suitable protection capacitors depends on the trace patterns on the board. In particular, the capacitor value may have to be modified when the circuit board design is changed. In actual testing, the LED negative voltage value will depend on the choice of the circuit board material as well as the wiring patterns.

In this approach, an additional protection capacitor is recommended. A transient electrical over stress during normal DC operation may attack a single LED because of the protection capacitances. For example, LED D4 in Figure 10 will only have stresses when a transient stress is applied. The additional capacitor that is located between cathode line and anode line will reduce the likelihood of electrical stress.

For thermal pad protection, a 0.1μF capacitor which is connected to the power supply line usually eliminates discharge at the LUXEON Rebel discharge gap as shown in Figure 11. With this protection capacitor, the voltage between anode/cathode and thermal pad is less than a couple of volts in the simulation and discharge is not likely to happen.

In conclusion, a protection device is helpful to reduce electrical overstress during the isolation test. This protection circuit is recommended to ensure optimum LED reliability in the application.

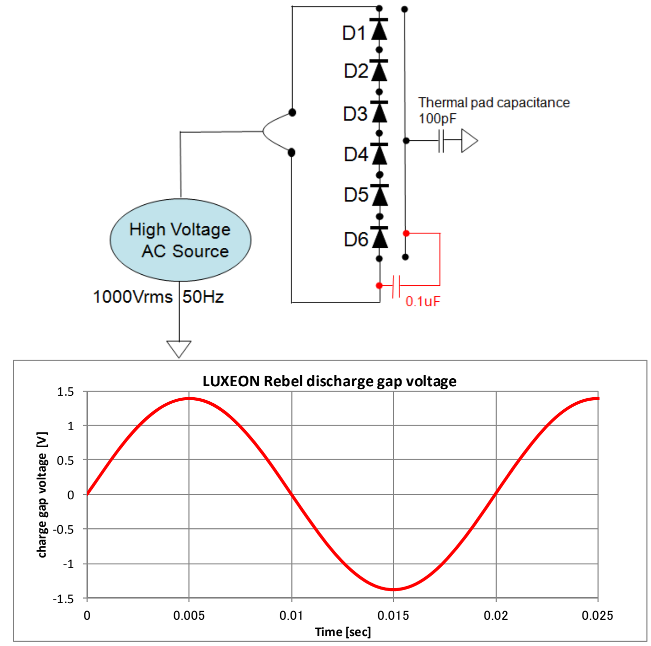


Figure 11. Discharge gap voltage with thermal pad protection.

7. High Voltage Drivers

Some customers prefer large series strings of LEDs connected to a driver with a high voltage output. Though there is nothing fundamentally wrong with this practice, above recommendations will not be sufficient. We recommend electrically separating the thermal pads of the LED's to prevent a current path through the common thermal pad connection, as shown in Figure 12.

In the top drawing of Figure 12, we assume 80 LEDs in series; in this configuration all LEDs have their thermal pads electrically connected through some common copper plane. As in most cases, this common plane is isolated from ground, i.e. it is electrically "floating". With 80 LEDs, the voltage across the string is typically 240V. Assuming full symmetry, the common thermal pad plane can be expected to float at approximately 120V. That puts 120V DC across the arc gap of the first and last LED in the string. It will take very little in terms of moisture or dust for such an arc gap to break down, causing temporary current spikes, which might be destructive. Separating the thermal pads electrically allows each thermal pad to "float" to a voltage determined by its stray capacitance. Better yet, the thermal pad of each LED can be electrically connected to the anode or cathode of the LED so that the voltage of each thermal pad is fixed.

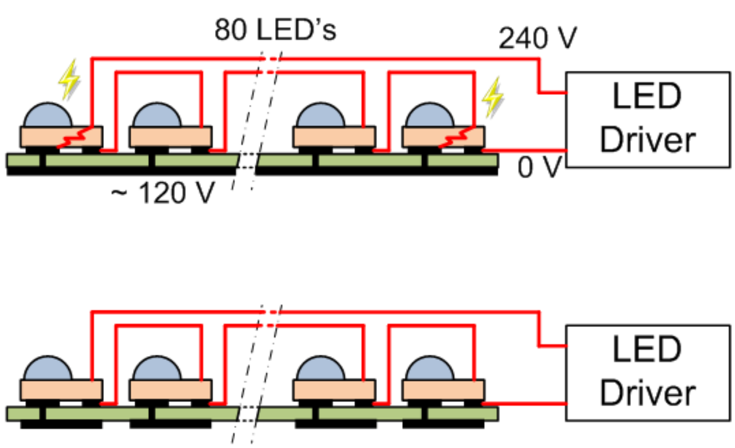


Figure 12. Electrically separate thermal pads.

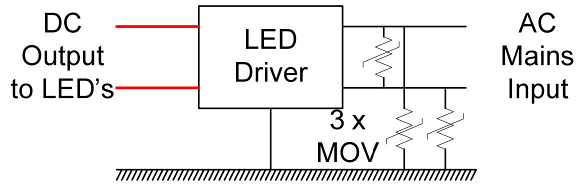


Figure 13. Protection against line transients and lightning strikes.

8. Lightning Strikes and Line Transients

When designing an LED Luminaire, careful consideration should also be given to the effects of lightning strikes and line transients. As stated earlier, any differential mode impact of such events is typically prevented by the driver. To prevent high common mode currents, line transient suppression at the AC mains input with metal oxide varistors (MOVs) is recommended (Figure 13). The dimensioning of the MOVs will be entirely determined by the specifics of the luminaire design and the protection ratings that need to be met. A safety approved MOV is recommended to simplify the safety tests.

The likelihood of LED failures due to line transients can be significantly reduced by minimizing the stray capacitance of the thermal pads and by electrically separating those pads.

9. Recommendations

The likelihood of electrical stress in an LED application can be reduced by taking the following recommendations into account during the design of the application:

- Minimize the capacitance of circuit board traces to ground by eliminating all unnecessary copper surfaces on the top of a double sided FR4 board or the circuit layer of a MCPCB/IMS board. The surface area around a thermal pad does not have to be larger than 3mm outside of the LED package. Increasing the copper area does not significantly improve heat spreading, but does increase parasitic capacitances.
- Keep board traces at least 2mm away from the board edge in an MCPCB/IMS board and at least 2mm away from any grounded surface to prevent arcing during isolation tests.
- When using FR4 boards, try to keep the thermal pads of the LEDs electrically "floating" and separated from each other, or connect them to either anode or cathode. This will minimize the voltage difference between anode/cathode and the thermal pad, thereby minimizing the possibility of electrical discharge across the LED body.
- Add bypass capacitors and discharge protection capacitors whenever possible.
- Provide an MOV pack at the mains input of the luminaire to prevent transients and lightning strikes from damaging the LED array.
- NEVER hot-swap LED boards. Always switch off the power supply or driver before disconnecting and reconnecting an LED array.
- Use common ESD protection methods during manufacturing and installation of LED luminaires (e.g. ankle-straps, wrist-straps, conductive mats etc.).
- Isolation tests are not required if an isolated power supply is used and the output is SELV (< 60V DC). This can be accomplished by reducing the number of LEDs in series in a single string.

About Lumileds

Lumileds is the global leader in light engine technology. The company develops, manufactures and distributes groundbreaking LEDs and automotive lighting products that shatter the status quo and help customers gain and maintain a competitive edge.

With a rich history of industry "firsts," Lumileds is uniquely positioned to deliver lighting advancements well into the future by maintaining an unwavering focus on quality, innovation and reliability.

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