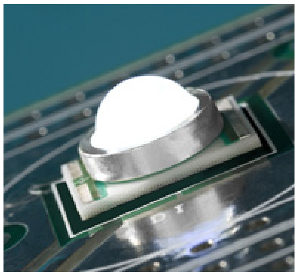
Cree® XLamp® LEDs



INTRODUCTION

This application note describes electrical overstress (EOS) events, their effect on Cree XLamp LEDs and some simple methods of protecting XLamp LEDs against EOS. Electrical overstress is simply exposing an LED to any current greater than the maximum current specified in that LED's data sheet. The number or length of EOS events is irrelevant because any single EOS event can cause damage to the LED. This damage can be exhibited either in an immediate failure or a failure many hours after the EOS event.

This application note assumes that primary protection circuits are already implemented in the power supply or in other protection systems to prevent damages from lightning strikes, power surges, power crosses, and so on. This application note will focus on secondary protection circuits to protect LEDs against EOS events that are commonly seen in practice. Please note that this document is not a complete guide on secondary protection circuits.

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CAUSES OF ELECTRICAL OVERSTRESS

The main causes of electrical overstress of LEDs are:

1. Electrostatic discharge (ESD) events

ESD is a widely recognized hazard during manufacturing, shipping and handling of many semiconductor devices. All XLamp LEDs contain ESD protection devices and are classified as class 2 in the MIL-STD-883 Human Body Model, meaning they will survive 2kV ESD events. While XLamp LEDs have protection, it is still possible to induce EOS damage via ESD events.

2. Transient over-current events

Transient over-current events are events that subject the LED to current that is higher than the maximum rated current on the LED data sheet, either directly through high current or indirectly through high voltage. These events are transient, meaning they happen for a short period of time – typically less than one second. These events are sometimes referred to as "spikes," as in "current spike" or "voltage spike."

If the over-current event occurs immediately when the LED is turned on or plugged into a energized power supply (also called "hot plugging"), this over-current event is called "in-rush current."

3. Over-driving the LED

In the case of over-driving, the LED is being constantly driven over the maximum rated current due to the driver circuit design, whether intentional or not. Since this is a design choice made in the LED driver circuit, this application note will not address protection circuitry for this cause of EOS.

EFFECTS OF ELECTRICAL OVERSTRESS ON XLAMP LEDS

It is impossible to predict the failure mode of every LED exposed to electrical overstress, but Cree has seen two common symptoms of XLamp LEDs that have had an EOS event cause a catastrophic LED failure.

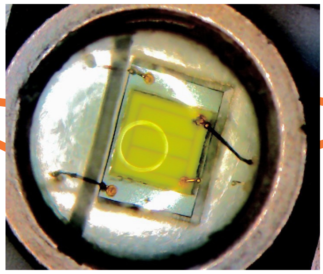
Damage to Bond Wires

One common failure mode from EOS is damage to the bond wires inside the LED package, as illustrated in Figure 1 below. This damage usually occurs as a burned wire or a broken wire. In addition, the EOS event can cause damage to other materials in close proximity to the bond wires, such as the encapsulant or phosphor.

Damage Near Bond Pads

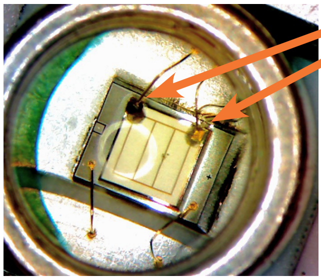
Another common failure mode from EOS is damage to the LED chip itself near the bond pads, as shown in Figure 2 below.

Burned wires



Broken wires

Figure 1



Damage near bond pads

Figure 2

CLASSES OF EOS PROTECTION DEVICES

There are two main categories of devices that help protect LEDs from electrical overstress: over-voltage protection devices and current limiters.

Over-voltage protection devices

Over-voltage protection devices are connected in parallel to the electronic equipment to be protected (Figure 3). These devices are designed to stay off in standard working conditions to avoid any influence with the other electronics circuits and to minimize the over-voltage when an EOS event occurs.

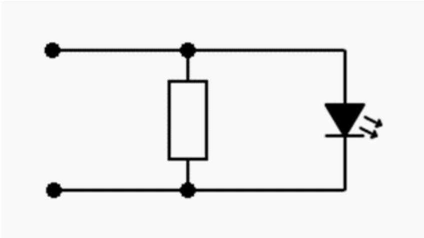


Figure 3

Over-voltage protection devices are divided into two families: clamp devices and crowbar devices. Both types of device are available in unidirectional or bidirectional working directions. The I-V curves for these two devices are illustrated in Figure 4 (right).

Device	Behavior	Design Challenge
Clamp devices	Limit (or "clamp") the voltage at a defined value during an EOS event	Power dissipation during the EOS event, since the clamp voltage can be large.
Crowbar devices	Attempt to create a short circuit when the device's trigger voltage is reached	Crowbar short-circuit protection should turn off once the EOS event is removed.

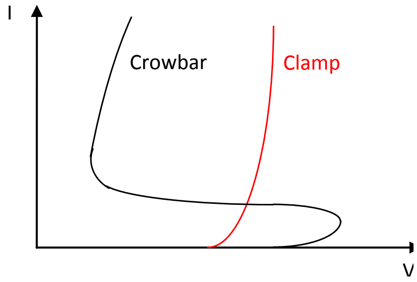


Figure 4

Current limiter devices

Current limiter devices are connected in series to the electronic equipment to be protected (Figure 5). As the name suggests, these devices are designed to limit the current passing trough to a specified current.

Current limiter devices are divided into two families: one-time devices and resettable devices.

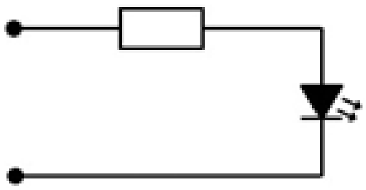


Figure 5

Device	Behavior
One-time devices	Create an open-circuit during EOS event. The device must be replaced to restore the circuit to original condition.
Resettable devices	Change resistance value during an EOS event. Removing the EOS or switching off the power supply will restore the device to its original state.

Cree recommends the use of resettable current limiter devices because they control the current directly and match the low maintenance characteristics of XLamp LEDs.

ESD PROTECTION

As mentioned previously, all XLamp LEDs contain ESD protection devices. This level of ESD protection should be sufficient for standard surface-mount production and handling procedures. Nevertheless, certain applications may require higher levels of ESD protection than what the XLamp LED provides.

There are two types of ESD suppressor devices, both over-voltage clamp devices: transient voltage suppressors (TVS) and multilayer varistors. Understanding the following key parameters (Figure 6) will aid in selecting these ESD suppressors.

Parameter	Meaning	Description
V_{RM} / V_{RWM}	Stand-off voltage	For V <= V_{RM}, the device is high impedance and will have very low leakage current
I_R / I_{RM}	Leakage current	Current that leaks through device when it is in the "off" state (less than 10 µA)
V_{BR}	Breakdown voltage	Voltage at which the device starts to conduct, measured at a specific current (typically 1 mA or 10 mA)
V_C / V_{CL}	Clamping voltage	Maximum voltage drop across device at the specific current I_{PP}
I_{PP}	Peak pulse current	Maximum current the device withstand without damage. Value depends on the specific waveform used for test.

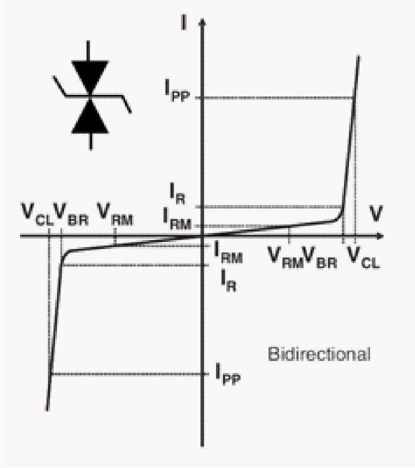


Figure 6

ESD suppressors must be used in parallel to each LED to protect each pin of the LED from ESD events (Figure 7). The devices should be selected so that VBR is greater than the maximum forward voltage of the LED used. For example, the maximum voltage of an XLamp XR-C cool white LED at 350 mA is 4.0 V, so the ESD suppressor should have VBR > 4.0 V. Depending on the circuit topology, layout and devices used, the circuit could survive higher ESD events (i.e., a 4kV transient) with no damage to the LED.

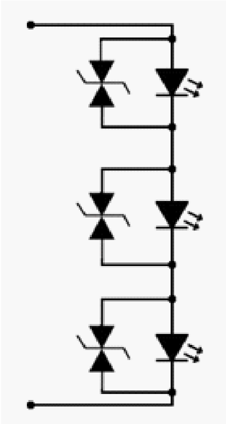


Figure 7

OVER-VOLTAGE PROTECTION

Over-voltage events to LED arrays can happen frequently – during LED fixture handling, installing and maintenance. One way to protect LED arrays from these events is to put an over-voltage protection device in parallel to the LED array (Figure 8). As already discussed in the ESD Protection section, transient voltage suppressors (TVS) are a good choice to limiting over-voltage events.

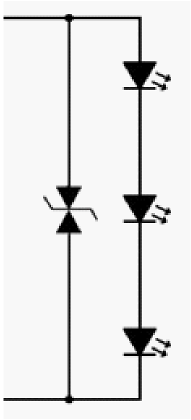


Figure 8

However, in this application, since the TVS is protecting the entire array of LEDs instead of just one, the breakdown voltage (VBR) of the device selected must be higher than the maximum voltage of the entire LED array for the intended operating current of the fixture. This value will depend on the LEDs used and the connection configuration used in the LED array. For example, 3 XLamp XR-C cool white LEDs in series at 350 mA would have a maximum voltage of (3 * 4.0 V) = 12.0 V.

Cree does not recommend using only over-voltage protection because most LEDs have forward voltages closer to the typical value and not the maximum value. An over-voltage event that is limited to the maximum voltage by a TVS device may still cause an over-current condition with the LEDs due to the variation of I-V characteristics of LEDs.

OVER-CURRENT PROTECTION

As discussed in the Classes of EOS Protection Devices section, resettable over-current devices are recommended as the best option for protecting LEDs from over-current events. Resettable over-current devices are based on Positive Temperature Coefficient resistors (PTC). These devices increase their resistance when temperature increases, either through the device's own power dissipation or by an increase in ambient temperature. A PTC device in series with an LED array (Figure 9) will decrease the current to the LEDs in an over-current situation.

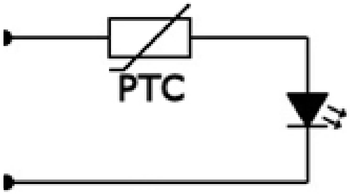


Figure 9

The key parameters of PTC devices are:

Parameter	Meaning	Description
I_R / I_{HOLD}	Rated current / Hold current	In 25ºC ambient, maximum current of device before switching to increasing resistance. In practice, this value will have to be de-rated to the maximum ambient temperature of the fixture.
I_{SW} / I_{TRIP}	Switch current / Trip current	In 25ºC ambient, minimum current of device before switching to increasing resistance. In practice, this value will have to be de-rated to the maximum ambient temperature of the fixture.
V_{MAX}	Maximum voltage	In 25ºC ambient, maximum voltage allowed.
I_{MAX}	Maximum current	Maximum current allowed during VMAX conditions.

The maximum voltage, maximum current and maximum ambient temperature of the LED array should be considered to help select the appropriate PTC product family. Next, the rated current of the PTC's product family should be de-rated according to the maximum ambient temperature to select the specific product that will remain off under normal operating conditions.

Using PTC for current limiting has challenges. First, the switch current can be two (or more) times the rated current, so the allowed LED current during an EOS event could still be more than maximum LED drive current. Second, the PTC device must warm up to offer the over-current protection, which can take hundreds of milliseconds to seconds before over-current protection is achieved. Based on these challenges, the use of PTC resistors for over-current protection is most useful when the normal operating current is small relative to the maximum current of the LEDs used.

PASSIVE IN-RUSH CURRENT PROTECTION

As described in the Causes of Electrical Overstress section, one common form of over-current event occurs when LEDs are connected to an energized power supply or when the power supply is first turned on. This event is called in-rush current. In-rush current protection can be implemented either with a passive solution (discussed in this section) or with active protection (discussed in the next section).

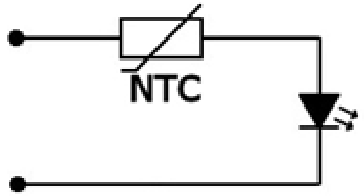


Figure 10

Devices called Negative Temperature Coefficient resistors (NTC) provide passive in-rush current protection. NTC resistors are complementary devices to the PTC resistors discussed in the previous section. NTC resistors come in two basic classes: high resistance and low resistance. High resistance devices are commonly used for performing thermal measurements. Low resistance devices are commonly used for in-rush current protection. Specifically, during a power supply hot-plug or initial power-up, the NTC devices present a high resistance value that protects the LEDs from in-rush current. After the device's transient time, the NTC resistor will turn on and resistance will be negligible.

Figure 11 (below) shows an example of in-rush current without and with NTC device protection.

The key parameters of NTC devices are:

Parameter	Meaning	Description
R_R / R	Rated resistance	In 25ºC ambient, resistance of NTC in off state
I_{MAX}	Maximum current	In 25ºC ambient, maximum continuous current
$B_{25/xx}$	Temperature coefficient	Used to calculate the NTC resistance at a specific temperature
C_{TEST} / C_{MAX}	Energy absorption capacity	Typically specified for 230 V_{RMS} or 110 V_{RMS}

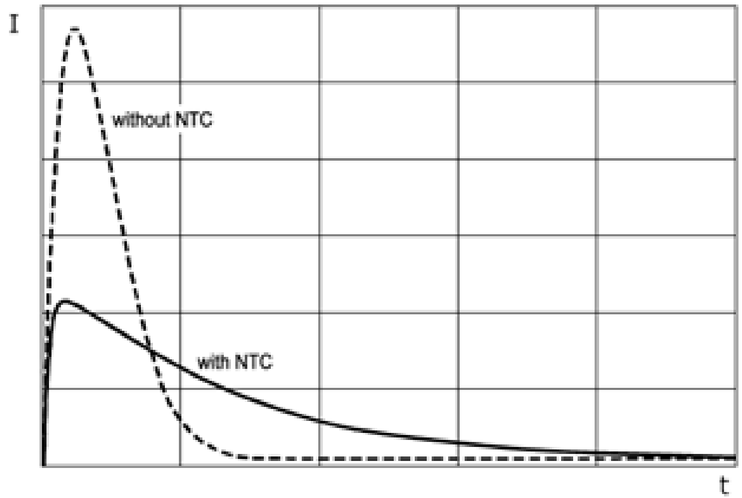


Figure 11

PASSIVE IN-RUSH CURRENT PROTECTION (CONTINUED)

To choose the best NTC for the application, find the maximum output voltage of the power supply and the typical voltage used by the LEDs at their normal operating current. Using the difference between the two voltages and the resistance of the NTC, the initial peak current can be calculated with the following formula:

$$I_{NTCpeak} = (V_{outputMAX} – N*V_F) / R_{NTC}$$

Where R_{NTC} is the NTC resistance at ambient temperature of 25ºC.

Most applications will have ambient temperatures different than 25ºC, so the correct NTC resistance should be calculated with the following formula:

$$R_{NTC} = R_R * e^{B*(1/T – 1/TR)}$$

Where B is the NTC resistor's temperature coefficient and temperatures are in Kelvin (K).

NTC Resistor Design Example

For this example, the ambient temperature will be assumed to be 40ºC and the following NTC parameters will be used:

- R_R = 33 ohm
- I_{MAX} = 1.3A
- $B_{25/100}$ = 3000
- C_{TEST} = 100µF at 230V

This example NTC resistor has the following resistance at 40ºC ambient:

$$R_{NTC} = 33 * e^{3000*(1/313.15 – 1/298.15)} = 20.4 \text{ ohm}$$

The LED array contains 3 LEDs connected in series with typical forward voltage of 3.3 V at 350 mA.

$$I_{NTCpeak} = (24 – 3*3.3)/ 20.4 = 0.69 \text{ A}$$

The calculated INTCpeak of 0.69 A is smaller than the example NTC resistor's IMAX of 1.3 A. Therefore, the NTC selected will work properly.

To save money and board space, one could find another NTC with the same R and B values but with a lower IMAX - since IMAX will only be violated for a short time during hot-plug or initial power-on conditions. For example, consider an NTC with the same parameters as the above example, but with IMAX = 0.5 A. Under normal drive current of 0.35 A, the NTC resistor is still within specifications, but the INTCpeak is greater than specification. To check if the NTC will work for the short time with the in-rush current, the CTEST value of the NTC resistor must be used.

First, use the capacitor energy formula to calculate the maximum energy from the in-rush current:

$$E = ½ * C * V^2$$

$$E = ½ * 100e-6 * 230^2 = 2.7 \text{ J}$$

Next, use the formula backwards to calculate the equivalent capacitance at 24 V:

$$C = E * 2 / V^2$$

$$C = E * 2 / (V – 3 * VF)^2 = 2.7 * 2 / (24 – 9.9)^2 = 27mF$$

If the power supply capacitors are smaller than the calculated value, then the smaller NTC can be used without issue. For this example, since the calculated capacitance is so high, the cheaper NTC resistor can be used in the application.

PASSIVE IN-RUSH CURRENT PROTECTION (CONTINUED)

Challenges with Passive In-Rush Current Protection

Using NTC resistors for passive in-rush current protection presents two design challenges. First, when the power is removed from the LED fixture, the NTC resistor cools down after a period of time (generally 30 seconds through 2 minutes after power down) and it is not as capable of limiting in-rush current. Therefore, if in-rush current events are expected to occur around 1 minute or so apart, the NTC resistor does not offer very effective over-current protection.

Second, the energy dissipation of the NTC resistor will reduce the total efficiency of the LED fixture. The amount of energy loss through the NTC resistor will depend on ambient temperature and drive current used, but this loss can be significant. The NTC resistor is a good solution with many LEDs in series and with a maximum power supply voltage not much greater than the maximum forward voltage of the LED array.

ACTIVE IN-RUSH CURRENT PROTECTION

For power supplies with high maximum output voltages or with requirements for the highest possible efficacy, active in-rush current protection may be a better option than using passive devices. Active in-rush current protection circuits have on-state resistance of just a few milliohms (instead of several ohms) and reset within milliseconds instead of minutes. This protection can be implemented with a MOSFET & TVS circuit (Figure 12) or with a dedicated in-rush current limiter device.

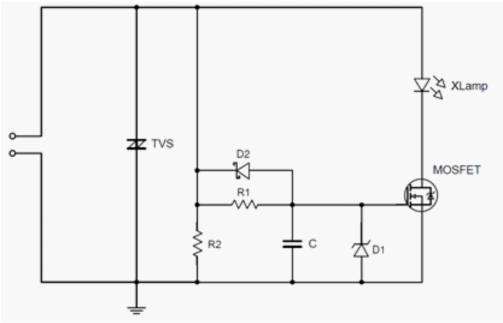


Figure 12

To demonstrate the advantage of the active in-rush current protection circuit, Cree conducted a worst-case scenario with and without the protection circuit in place. The worst-case test was to hot-plug an LED driver designed to power 12 LEDs in series at 350 mA into just a single LED. This specific power supply used had an open-circuit output voltage of 49 V. Figure 13 shows the results of hot-plugging this power supply into a single LED. The LED was exposed to peak current of 12.0 A and was driven over the target current for 20 ms. This is a typical EOS condition caused by in-rush current, which can cause a catastrophic failure and will ultimately compromise the long-term reliability of the LED.

By contrast, Figure 14 shows the result of hot-plugging the same power supply to the same LED with the in-rush current protection circuit in place. The power supply current does not exhibit a large current peak and reaches the target current within 200 ms.

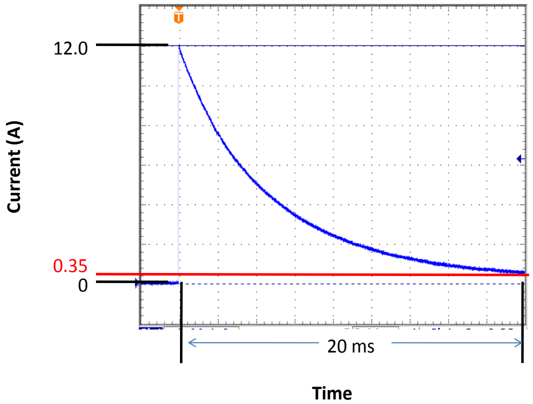


Figure 13

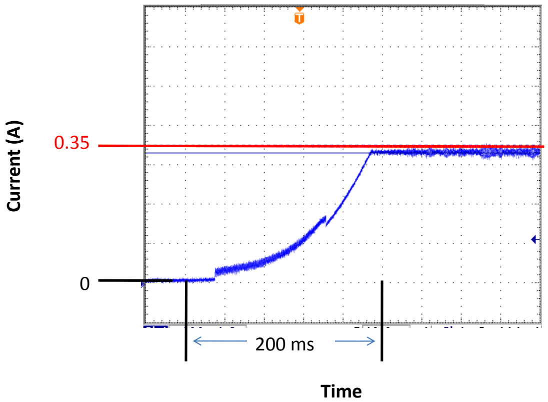


Figure 14

ACTIVE IN-RUSH CURRENT PROTECTION (CONTINUED)

This test confirms that the addition of a few components can be very effective in protecting the LED array from a large current spike due to in-rush current. The huge increase in end-product reliability should justify the small additional cost for the components. The one technical limitation of this protection circuit is that it cannot be used with LED circuits with pulse-width modulation (PWM) dimming.

CONCLUSION

Proper fixture design is the key to making a successful product in the growing LED lighting market. Most LED circuit designers are aware of good thermal, optical and electrical design principles, but may not have considered adding protection circuits to guard against improper usage or hot-plugging. Not every application will need electrical overstress protection, and adding such protection will add cost to the design and possibly decrease efficiency.

Nevertheless, Cree strongly recommends adding some level of protection to LED modules that do not include an on-board power supply to minimize the risk of an in-rush current event from the separate power supply. Installers accustomed to traditional lighting products that can handle hot-plugging may accidently cause LED light fixture failures by hot-plugging the LED array to the power supply. The use of a simple protection circuit with small cost can dramatically reduce the rate of returns from customers.