LED Failure Modes

In recent years, LED devices are being used increasingly as lamps due to their compactness, longevity and excellent efficiency. However, these electronic components are essentially semiconductor devices, and understanding how they work and how they fail is very different from conventional incandescent and fluorescent lights. This document describes the faults that can arise when LED devices are used.

Types of LED Fault

Incandescent and fluorescent lights most often fail to light due to a break in the electrical circuit caused by a snapped filament, but this problem hardly ever arises in LEDs provided they are used appropriately. The lifespan of an LED is normally defined as the time until its luminous intensity declines to 50% (or 70%) of its initial level. Even after this point, the luminous intensity of the LED simply continues to decline and there are rarely instances where there is clear electrical non-conductivity. However, in actual use, problems can arise for a variety of reasons. The problems that affect LEDs can be classified according to the failure mode, as shown below

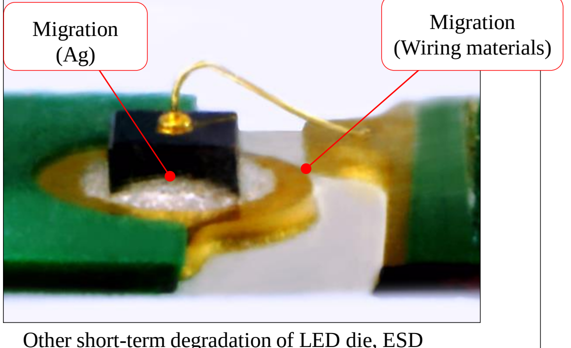
(1) Electrical leak or short-circuit
(2) Electrical discontinuity
(3) Abnormal loss of luminous intensity
(4) Other specific faults

(1) Electrical leak or short-circuit

Electrical leaks, short-circuits and electrical leaks that involve short-circuits are some of the more likely faults that occur in LED devices. Unlike faults in conventional incandescent and fluorescent lights, these faults involve short-circuits and can place a burden on the drive circuit. For this reason, the drive circuit must be designed so that the power supply capacity and the power permitted by the load-limiting resistor allow for situations where a short-circuit occurs. (Fig.1)

Fig.1 Examples of electrical leaks and short-circuits

Short-circuit due to migration in a surface mount LED



Other short-term degradation of LED die, ESD breakdown, etc

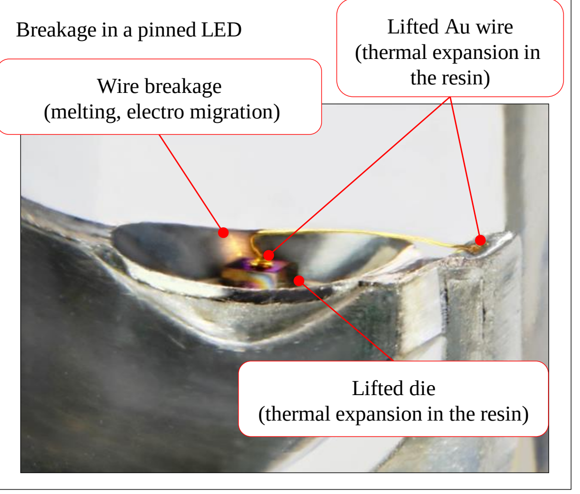
Electrical leaks and short-circuits are caused either by faults or degradation in the semiconducting properties of the LED die, or by electrochemical changes in the materials used.

(2) Electrical discontinuity

This occurs when there is a wire breakage inside the lamp. The main causes of such breakages are usually electromigration, wire breakage or separation due to internal stress, or a blowout in the bonding wire due to excessively large current.(Fig.2)

Fig.2 Examples of electrical discontinuity

Breakage in a pinned LED

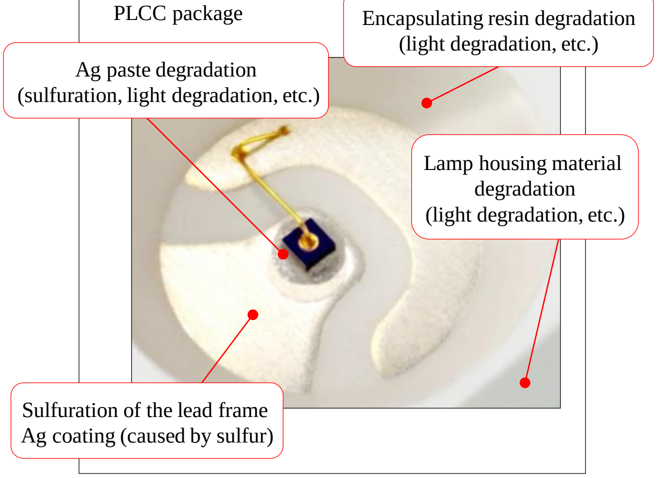


(3) Abnormal loss of luminous intensity

LED device development includes a range of reliability tests to confirm the lifespan of the proposed product, but depending on the actual operating environment, the luminous intensity of the LED may decline far more quickly than the design values. This is mostly caused by rapid deterioration of the LED component materials due to special environmental conditions and consequent absorption of the light from the LED die.(Fig.3)

Fig.3 Example of abnormal material degradation

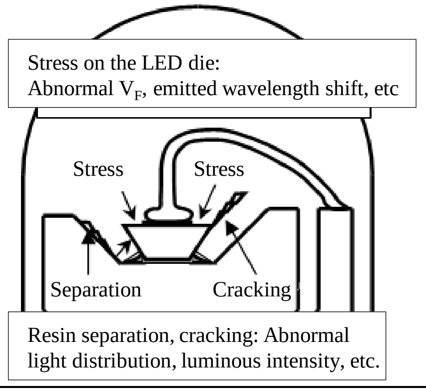
PLCC package



(4) Other specific faults

Even where there is no loss of luminous intensity, other properties of an LED device can change significantly, such as the light distribution, chromaticity and forward voltage. These are also due to the changes in the characteristics of the component materials discussed in the previous section. (Fig.4)

Fig.4 Example of special abnormalities due to stress in the resin



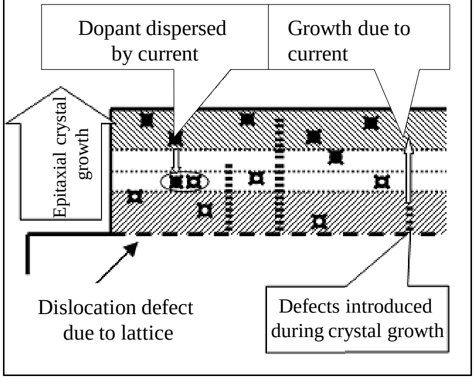
The next section looks in more detail at the failure modes, particularly with regard to the problems and changes in materials.

LED die Faults

Light intensity decrease due to powering up

LED die are a type of electrical device referred to as diodes and are basically constructed of joined p-type and n-type semiconductors that have different modes of electrical conductivity. (The join between the semiconductors is referred to as the p-n junction.). Positively charged holes in the p-type semiconductor and negatively charged electrons in the n-type semiconductor form the carrier for an electric current. The intracrystalline recombination of these holes and electrons results in energy being emitted in the form of electromagnetic waves, which are projected outwards as light.

Fig.5 LED die defects



However, there are in fact a number of factors that impede this process, the primary problems being intracrystalline defects and the presence of impurities.

(1) Intracrystalline defects (lattice defects and dislocation)

The quantum-mechanical action of electrons in solid crystals gives rise to unique characteristics in semiconductor devices, and LED die are no exception to this. In crystals, the atoms that comprise solids are arranged in regular patterns, but any irregular arrangements impair the solid's electrical conductivity and light emissions. These irregularities are referred to as defects or dislocations. The light-emitting portions of an LED die are normally highly crystalline single crystals that are manufactured using epitaxial crystal growth techniques. However, the growth process always introduces a number of defects. Defects introduced in the initial stages of LED die manufacture tend to grow larger when current is applied to light the LED. These results in problems such as increasing leak current and declines in light-emission efficiency, which impair the performance of the die. Defect growth is affected by factors such as the operating temperature and the stress applied to the die. The speed of defect growth increases with the severity of these factors.

(2) Impurity dispersion (doping)

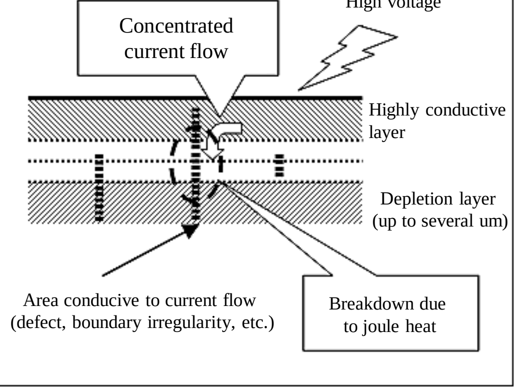
While impurities contained in crystals are also a type of defect, p-type and n-type semiconductors are high-purity semiconductor crystals into which minute amounts of impurities (referred to as dopants) are deliberately mixed when they are made. For example, gallium phosphide (GaP), which is well-known as a material used for LEDs, has no electrical conductivity in its pure crystalline form. However, when doped with minute amounts of zinc (Zn), the gallium is partially replaced by zinc and electron holes occur. Doping with silicon replaces the gallium with silicon, generating surplus electrons. The electrons and electron holes generated can move freely inside the crystal, giving the p-type and n-type semiconductors electrical conductivity. The LED die is built by using the semiconductors to form a p-n junction. This creates a zone at the joint interface in which the p-type and n-type impurities co-exist. The mixing of impurities not only leads to increasingly high resistance through carrier compensation, but also generates a tendency for complex defects to form. This results in recombination that is not accompanied by light radiation as well as defects that promote electrical leaks. And because impurities in semiconductors are transferred by electric fields and heat, this mixing progresses over time. This mixing zone frequently occurs in the area where electrons and electron holes recombine (known as the active layer), resulting in increasing numbers of defects in the active layer.

In this way, current flowing through an LED die gradually increases the number of defects in the active layer, while there are also progressive increases in the amount of leak current, decline in V_F and loss of emitted light output. The rate of deterioration varies depending on the operating temperature and the amount of stress.

Electrostatic breakdown

At the p-n junction interface, the carriers in the respective areas move between the areas as they are dispersed by heat. This results in charge compensation in an area close to the interface, generating a layer with no carrier that is referred to as the depletion layer. Because the mutual dispersal of the carriers is limited by the internal electrical potential generated by that dispersal, the depletion layer is normally no more than several microns thick. However, static electricity at the level generated by the human body reaches levels between several thousand and several tens of thousands of volts. If an LED is exposed to this voltage, almost all of the voltage is applied to the uncharged depletion layer. Because the depletion layer is extremely thin, the electric field becomes very intense and is sufficient to overcome the electrostatic resistance of the material. If the electrostatic resistance is exceeded, the discharge causes the energy stored in the depletion layer interface to be released as heat. However, this does not occur uniformly across the p-n junction and the discharge begins sooner in those sections with lower electrostatic resistance, so that the stored energy is focused in those locations. As a result, the material in those locations changes, with perforations forming in the p-n layer in areas with high conductivity so that the p-n junction undergoes localized breakdown. For this reason, LEDs generally fall into short-circuit mode following electrostatic breakdown. If high voltage is again applied to an LED in this condition, current flows first to areas with high conductivity and the resulting heat causes vaporization in those areas so that the p-n junction very rarely recovers. However, because the non-uniform state of the interface is maintained, there is a greater likelihood that the short-circuit defect will recur.

Fig.6 LED die electrostatic breakdown



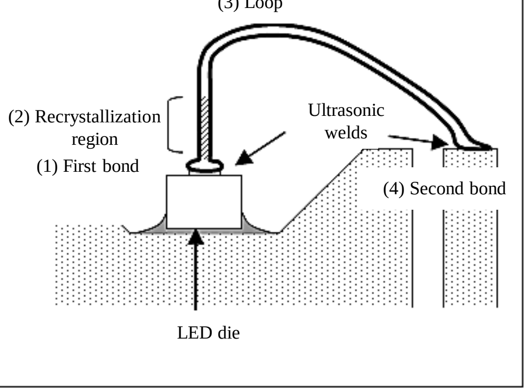
Electrode corrosion or separation

Two functions are demanded of LED die electrodes. One is their role as a terminal to channel an external power supply. In this role, terminals generally consist of a bonding pad made using gold, since their function is to provide a connection point for gold wire. The other function is to efficiently convey electricity to the semiconductor, and different materials are normally used for the p-type and n-type semiconductors. Depending on the combination of materials used, there can be a significant voltage drop at the junction between the semiconductor and the metal, and only a limited number of combinations provide a contact with low electrical resistance. Electrodes that provide a contact with low electrical resistance are called ohmic electrodes. Typical examples of ohmic electrodes are gold and germanium on p-type semiconductors and aluminum on n-type semiconductors. Other materials such as nickel, titanium, tungsten and palladium are used to improve contact adhesion and prevent interdiffusion. The presence of moisture among these materials can facilitate corrosion or oxidation and result in high levels of resistance. The latest LEDs use a passivation layer and encapsulating resin to prevent contact with external moisture, but the diffusion of moisture in hot and humid atmospheric conditions cannot be ignored. There is a still a risk of LEDs failing to light due to electrical discontinuities or abnormal increases in forward voltage caused by electrode corrosion or separation, so the operating environment conditions must be considered carefully.

Bonding Wire Defects

The bonding wire connects the lead frame to the LED die electrode. Gold wire is the most commonly used material for the bonding wire, since it supplies power to the LED die. Because gold is a malleable metal, it can easily be bonded to the LED components using ultrasonic welding. Once welded into place, the gold wire can be divided into 4 sections in accordance with the bonding procedure. (Fig.7)

Fig.7 Bonding Wire



(1) First bond section
Just prior to welding, the tip of the gold wire forms a round ball. This ball is placed against the bonding pad and then pressed down onto the pad while being exposed to ultrasonic waves. This results in the wire being welded onto the bonding pad over a large area.

(2) Recrystallization region
A gold ball is formed when the tip of the wire melts due to heat applied to the tip of the gold wire by an electrical discharge. The section of wire immediately behind the ball is partially melted by the heat generated by the electrical discharge and is then cooled. This causes the metal to crystallize, forming a recrystallization region made up of a number of crystal grain boundaries. This makes this section slightly more rigid and brittle than the rest of the wire.

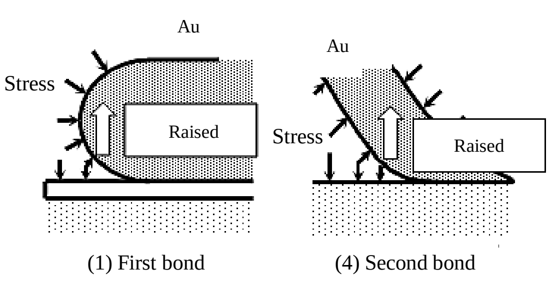
(3) Loop section
Because the wire beyond the recrystallization region is still malleable, the curve in the wire is formed in this section.

(4) Second bond section
After the first bond, the wire is drawn to the lead frame and held against it as ultrasonic waves are applied to weld the wire to the frame. The end of the wire is also pinched off.

Of the above sections, problems with wire breakages mostly occur in sections (1), (2) and (4).

Breaks due to internal stress in the encapsulating resin
Resin undergoes thermal expansion in response to temperature rises, and the resulting stress can have the effect of pulling the first bond and second bond section away from the die electrode or lead frame. Measures such as heat shock testing are used in product development to ensure that the product design is safe, but where extremely rapid temperature rises occur and the stress mitigation is insufficient, the strength of the weld between the gold wire and the other components may fail.

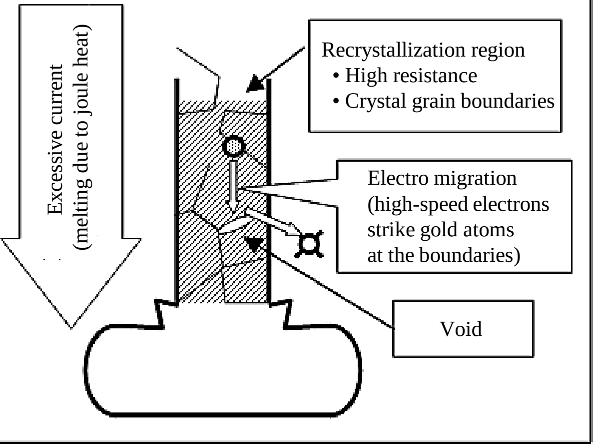
Fig.8 Stress on Au wire due to thermal expansion in the resin



Breaks due to acceleration
LED devices are normally entirely solid-state, so breaks caused by acceleration are unlikely unless there is an impact sufficient to destroy the entire device. However, in some metal-can-type devices, the interior is filled with an inert gas rather than being enclosed in resin. In such devices, it is possible for acceleration to place an excessive load on the gold wire and the wire can break, either due to the size of the load or due to repeated load application. Care must also be taken with devices that use non-rigid encapsulating resin and some high-power products where a gel-type resin is used just around the terminal to prevent internal stress in the encapsulating resin.

Breaks due to excessive current
There is electrical resistance in the gold wire, and it is easy to imagine that the joule heat generated by an excessively large flow of current might cause the wire to break. However, such heat generation is suppressed provided the time frame is short. Pulse Width Modulation (PWM), which is one of the methods used to drive LEDs, uses an intermittent pulse current to light the LED rather than a normal direct current (DC) flow. This method has the advantage of eliminating the current dependency of LED characteristics such as the emitted light wavelength, thereby offering greater stability. If the maximum current of the pulse is large and the time for which it is applied is short, the average current is kept low and heat-related problems can be avoided. However, this places restrictions on the maximum current. It is also possible for the bonding wire to break due to electromigration. This is particularly likely to occur in the recrystallization region of the gold wire where there are crystal grain boundaries.(Fig.9)

Fig.9 Wire breakage in the recrystallization region due to overcurrent



Die Bonding Problems

Separation due to internal stress in the encapsulating resin

As discussed in the section on the bonding wire, temperature increases cause the encapsulating resin to swell, which can result in stress capable of pulling apart the connections. This stress can also have the effect of pulling apart the LED die and lead frame. Where the die bonding resin is also used to supply power, as is normally the case in LEDs, the LED is unlit when the circuit is electrically open. Also, in lamps such as InGaN die where the die has electrodes with 2 p-n junctions on the top of the die and bonding wires supplying power to both, heat dissipation from the die to the lead frame is impeded and this can lead to significant decreases in performance when the drive current is large, though it does not cause the lamp to turn off immediately.

Separation of this sort is heavily dependent on the shape of the LED die and the type of die bonding. Accordingly, lamp design includes research into die shapes and internal structures that are tailored to the conditions in which the product will be used.

Die bonding resin deterioration

Because the die bonding material is close to the LED die, it is subjected to extremely high concentrations of light energy from the die. If the die bonding material is a resin, there is the risk of light degradation caused by the light from the die. For instance, if the device emits blue light and silver paste is used in the die bonding resin, the silver paste turns black when current is applied for long periods, leading to a severe degradation in the device's luminous intensity. This degradation is exacerbated by the presence of moisture.

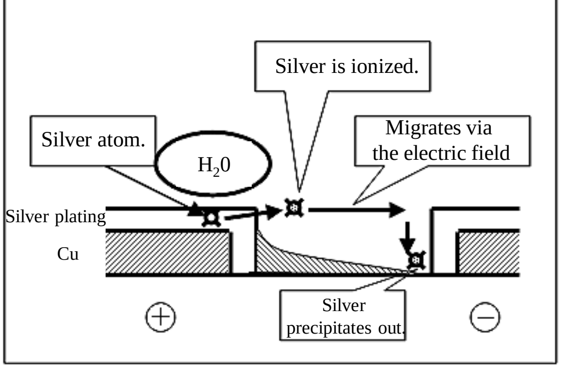
To prevent degradation of this sort, lamps may be designed so that eutectic bonding or gold bump bonding is used for die bonding instead of a resin. Even where silver paste is used, some products are made with a lifespan sufficient for the design purpose, but the ambient environment in which the product will be used must be carefully researched.

Migration

Migration is a phenomenon that occurs when electric fields exist among multiple metallic materials, and the metallic materials precipitate out and grow via the electric fields. The presence of moisture tends to accelerate this phenomenon. The silver contained in the silver paste normally used in die bonding materials is one of metals that is more susceptible to migration. (Fig.10)

When this is exacerbated by the presence of moisture, the possibility that any of a range of short-circuit events can occur must be considered. Because the die in an LED package is entirely embedded in the encapsulating resin, migration does not pose any immediate problems. However, the speed at which moisture disperses in the encapsulating resin increases exponentially relative to rises in temperature, and migration can become a serious problem when LEDs are used in environments where temperatures and humidity levels are high. For this reason, careful consideration must be given to the question of whether LED devices can be used in a given operating environment.

Fig.10 Silver atom migration



Encapsulating Resin Problems

Cracking due to internal stress in the encapsulating resin

As discussed above, expansion of the encapsulating resin due to temperature increases generates stress inside the lamp, and the application of stress to the various components can result in defects. Internal stresses also affect the encapsulating resin itself, and in extreme cases will cause the resin to crack. Cracking is largely dependent on the internal shape of the resin and can be avoided by taking steps in the design process. In PLCC-type lamps, because the structure is not supported by the encapsulating resin, the stresses caused by expansion can be alleviated by using flexible encapsulating materials. In pinned LEDs, gel-type resins are sometimes used to fill the area immediately around dies that tend to become hot.

Light degradation of the resin

Because the encapsulating resin is exposed to the light emitted by the die at very close range, some sections of the resin receive extremely high concentrations of light energy. So the problem of light degradation described in the section on die bonding resin also applies to the encapsulating resin. Silicon resin is one material with a high resistance to light degradation and is frequently used in devices that emit blue light.

Other Problems

The sections above have discussed faults and problems that arise in LED lamps. In the development of LEDs, considerable thought has been given to the likelihood of these problems arising and this has led to extremely reliable devices being designed for "normal operating environments". However, it is acknowledged that problems with LED lamps tend to occur more quickly in more unusual environments. For example, if LEDs are used in volcanic gas atmospheres, the hydrogen sulfide that is the major component of volcanic gas penetrates the resin and readily reacts with silver components in the lamp. The silver turns black as a result and the lifespan of the lamp is severely shortened. This problem is not limited to volcanic gases. Similar problems are likely to occur whenever sulfur components are expelled into a device that uses LEDs.
Other environments that are generally inhospitable to semiconductor devices, such as highly acidic or saline atmospheres, are also less than ideal for LEDs and cause abnormal levels of deterioration.
Moisture is a contributing factor to a range of faults, and there are also instances where moisture itself leads directly to device failure. Most LEDs are embedded in encapsulating resin, but resin typically tends to absorb moisture readily. If resin that has absorbed moisture is subjected to sudden temperature increases, such as those that occur during soldering, the moisture can sometimes erupt in a phreatic (vapor) explosion.