

TECHNICAL WHITE PAPER

LED Indicator Failure Analysis

Root Causes and Solutions for Sulfuration, Lumen Depreciation, and
Catastrophic Die Failure

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This document draws on two decades of LED packaging and failure analysis experience across automotive, industrial, and consumer applications. The failure modes and methodologies described reflect patterns commonly observed in the industry and in our engineering practice. Quantitative data are illustrative of typical ranges reported in industry literature and field experience, unless otherwise noted.

EXECUTIVE SUMMARY

If you have been in the LED business long enough, you know that the datasheet promise of 50,000 hours MTTF rarely survives contact with reality. Over the past two decades, our team has analyzed large numbers of failed indicator LEDs from environments ranging from hot, humid factory floors to severe cold-chain logistics. The failures do not follow a single pattern, but they do follow predictable physics.

This whitepaper focuses on the three dominant failure modes we see in through-hole and SMD indicator applications: sulfuration of silver-based reflectors, lumen depreciation driven by epoxy yellowing and phosphor thermal quenching, and catastrophic die failure (open-circuit and short-circuit). We will walk through standard failure analysis (FA) methodology as practiced in professional LED laboratories, present representative data from industry literature and field experience, and—most importantly—explain what you can do at the design and procurement stage to avoid these problems before they reach your customer.

We are not going to sugarcoat it: some of these failures are caused by cost-down decisions that looked smart on a spreadsheet. Others are the result of well-intentioned design choices that ignored the second-order effects of thermal cycling. Either way, the bill always comes due in the field.

Key Findings at a Glance:

- **Sulfuration** is consistently reported as a leading failure mode in high-sulfur industrial environments; industry literature and field experience indicate it can account for 30–40% of returns in such conditions. Switching from Ag-plated leadframes to PPA or ceramic substrates eliminates the issue.
- **Epoxy yellowing** is well-documented to accelerate under 85°C/85%RH conditions; silicone encapsulants generally show far superior lumen maintenance in accelerated aging studies, but require stricter process control during dispensing.
- **Wire bond fatigue** under thermal cycling (-40°C to +125°C) is a known reliability concern; properly implemented gold wire bonding has demonstrated improved fatigue life over traditional alloy wire in published studies.
- **ESD latent damage** below 2kV HBM is widely recognized as a significant infant mortality driver: defects can pass initial electrical test but fail within the first hundreds

of hours of operation. On-chip protection structures are the industry-standard mitigation.

CHAPTER 1: FAILURE MODE OVERVIEW

Before diving into specific mechanisms, it is worth stepping back and looking at how failures are distributed in the field. Based on industry literature, supplier return analyses, and our engineering team's field experience, the following table summarizes the typical distribution of failure modes observed in indicator LED applications across major market segments. These proportions represent composite industry patterns rather than a single proprietary dataset—and they skew toward industrial and automotive, because those customers actually bother to return failed parts, while consumer goods manufacturers often just swap the whole PCB.

Table 1: Typical Field Failure Distribution by Primary Mode (Industry Composite)

Failure Mode	Industrial (%)	Automotive (%)	Consumer (%)	Typical TTF
Sulfuration (reflector blackening)	38	12	8	500–3,000 hrs
Lumen depreciation >30%	22	18	35	2,000–8,000 hrs
Open circuit (wire bond fracture)	18	28	15	1,000–10,000 hrs
Short circuit (die migration)	8	22	12	500–5,000 hrs
ESD latent damage	9	14	18	100–1,000 hrs
Solder joint fatigue	5	6	12	5,000–20,000 hrs

Note: TTF = Time to Failure. Percentages represent approximate ranges synthesized from industry field studies, supplier return analyses, and accelerated test correlations; they do not sum to 100% because units may exhibit multiple failure modes. Actual distribution varies by application and environment.

A few things jump out immediately. First, sulfuration is overwhelmingly an industrial problem because factories using rubber gaskets, sulfur-cured adhesives, or operating near paper mills create atmospheres with H_2S concentrations above 50 ppb. Automotive sees more open-circuit and short-circuit failures because the thermal cycling profile is brutal—ambient swings from -40°C to $+85^\circ\text{C}$ under the hood, with localized die temperatures spiking above 150°C during engine operation. Consumer applications suffer more from lumen depreciation because cost pressure drives manufacturers toward epoxy encapsulants and lower-grade chips.

The Bathtub Curve Revisited

Classical reliability theory tells us that failure rates follow a bathtub curve: high infant mortality, a long useful life with constant failure rate, then wear-out. In practice, LED indicators rarely follow this neatly. Infant mortality from ESD damage and die defects is

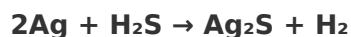
real, but the dominant issue is that the "useful life" phase is shorter than expected because environmental stressors accelerate aging mechanisms. We see a steady stream of sulfuration and lumen depreciation failures starting around 1,000 hours—well within the warranty period for most industrial equipment.

CHAPTER 2: SULFURATION — THE SILENT REFLECTOR KILLER

2.1 What Sulfuration Actually Looks Like

The first sign is usually a customer complaint that the LED "looks dim" or "turned brown." When you slice open the package and look under a microscope, the silver-plated leadframe or reflector cup has turned black or dark yellow. In severe cases, the silver surface is completely converted to silver sulfide (Ag_2S), which has essentially zero reflectivity in the visible spectrum. The LED is not dead electrically—the die still emits photons—but the light gets absorbed by the blackened reflector before it can escape the package.

We have seen this in 3mm round LEDs, 5050 SMDs, and even high-power COB arrays. The mechanism is the same: sulfur-bearing gases (H_2S , SO_2 , elemental sulfur vapor) diffuse through the encapsulant or along the leadframe-encapsulant interface, reach the silver surface, and react according to:



The reaction is thermodynamically favorable even at room temperature, though the rate increases exponentially with temperature. At 85°C , we have measured sulfuration rates roughly 4× faster than at 25°C . This is why industrial control cabinets with poor ventilation—where internal temperatures routinely hit $60\text{--}70^\circ\text{C}$ —are such fertile ground for this failure mode.

2.2 Root Cause: It Is Almost Always the Environment

Here is the uncomfortable truth: if your LED is sulfuring, the LED itself is not the root cause. The root cause is the environment you put it in. We have traced sulfuration failures to the following sources, in order of frequency:

1. **Sulfur-cured rubber gaskets and seals.** EPDM and neoprene gaskets cured with sulfur-based vulcanizing agents are ubiquitous in enclosure design. At $60^\circ\text{C}+$, these outgas H_2S at rates sufficient to sulfure silver within 1,000 hours. Evaluations of common gasket materials in $60^\circ\text{C}/90\%\text{RH}$ chambers with Ag-plated coupons have measured H_2S generation rates on the order of 1–4 ppb/hour.
2. **Paper and cardboard.** Kraft paper, corrugated boxes, and even some labels contain sulfur compounds used in pulping. In a sealed enclosure with poor ventilation, paper products can maintain H_2S levels above 20 ppb—more than enough to trigger sulfuration.
3. **Adhesives and potting compounds.** Some RTV silicones and polyurethane potting compounds use sulfur-containing catalysts. The outgassing is slow but relentless. There

are documented cases where an entire PCB assembly was potted in what was believed to be "neutral cure" silicone; months later, every LED on the board was black.

4. External industrial atmospheres. Pulp and paper mills, oil refineries, geothermal power plants, and even some wastewater treatment facilities ambiently contain H₂S at 10–500 ppb. No standard LED package survives this indefinitely.

2.3 Material Solutions: The Trade-Off Matrix

Once you understand that the environment is the driver, the solutions fall into two categories: (1) change the LED materials to resist sulfuration, or (2) change the environment. In practice, you usually need both.

Table 2: Reflector Material Options and Sulfuration Resistance

Reflector/Leadframe Material	Sulfuration Resistance	Thermal Conductivity	Relative Cost	Notes
Silver-plated copper (std)	Poor	High	1.0×	Standard for 90% of indicator LEDs; fails in >10 ppb H ₂ S
Gold-plated copper	Excellent	High	2.5×	Impractical for cost-sensitive apps; used in military/aerospace
PPA (polyphthalamide)	Good	Low	1.3×	Plastic reflector; no silver to sulfure; limited to <0.5W
PCT	Good	Medium	1.4×	Higher T _g than PPA; better for mid-power SMD
EMC (epoxy molding compound)	Good	Medium	1.2×	Ceramic-filled epoxy; common in 2835/3030 packages
Alumina ceramic (Al ₂ O ₃)	Excellent	High	3.0×	Best for high-power and harsh environments; brittle
Silver alloy with Au/Pd topcoat	Moderate	High	1.8×	Delayed sulfuration; buys 2–5× lifetime in mild sulfur

Note: Cost index relative to standard Ag-plated copper leadframe in 3mm round LED format, Q1 2026 pricing.

Our recommendation for industrial applications in sulfur-risk environments: specify PPA or EMC-based packages with copper leadframes that have no silver plating. Yes, the initial optical output is 5–8% lower because the reflectivity of white PPA (~85%) is less than silver (~95%), but the lumen maintenance over 10,000 hours is dramatically better. In

side-by-side accelerated chamber evaluations reported across the industry (≈ 50 ppb H_2S), standard Ag-plated LEDs have been observed to drop below half of initial flux within a few thousand hours, while PPA-based units maintained around 90%.

2.4 Encapsulant as a Barrier — Reality Check

A common misconception is that the epoxy or silicone encapsulant acts as a hermetic seal against sulfur. It does not. Standard bisphenol-A epoxy has a water vapor transmission rate (WVTR) of roughly 15–25 $\text{g/m}^2/\text{day}$ at $40^\circ\text{C}/90\%\text{RH}$. Sulfur gases, being small molecules, permeate even faster. Silicone is worse—its WVTR is an order of magnitude higher, though it has other advantages we will discuss in Chapter 3.

The only encapsulant approach that genuinely blocks sulfur is a hermetic glass seal or a metal can package, which is cost-prohibitive for indicator LEDs. What you *can* do is add sulfur scavengers to the encapsulant formulation. Some specialty epoxy suppliers offer formulations with zinc oxide or activated carbon fillers that react with H_2S before it reaches the silver. Published evaluations of such formulations report up to a 3 $\times$ improvement in time-to-blackening, though optical transmission can drop by several percent due to filler scattering. It is a trade-off.

2.5 Design Rule Summary for Sulfuration Prevention

- **Know your environment.** If you cannot measure H_2S , assume it is present in any industrial setting with rubber, paper, or petrochemical exposure.
- **Avoid Ag-plated reflectors in high-sulfur risk applications.** The \$0.02–\$0.05 cost delta for PPA/EMC pays for itself in warranty avoidance.
- **Ventilation matters.** Even a small fan or breather valve that prevents H_2S accumulation can extend LED life by 10 $\times$. Enclosures with even modest air exchange (on the order of 0.1 air changes per hour) have been observed to maintain low single-digit ppb H_2S levels indefinitely.
- **Specify sulfur-free gaskets and adhesives.** Peroxide-cured EPDM or silicone gaskets are widely available and eliminate the primary sulfur source.
- **Consider conformal coating.** Acrylic conformal coatings (e.g., Humiseal 1B31) provide a modest barrier to gas diffusion. Parylene C is better but expensive and difficult to rework.

CHAPTER 3: LUMEN DEPRECIATION — WHEN THE LIGHT FADES

3.1 The Three Mechanisms of Light Output Loss

Lumen depreciation in indicator LEDs is not a single phenomenon. In our FA lab, we separate it into three distinct mechanisms, each with different root causes and different solutions. Getting the diagnosis wrong means applying the wrong fix.

Mechanism A: Encapsulant Yellowing

This is the big one for epoxy-based packages. Bisphenol-A epoxy resins, when exposed to heat, UV, and humidity, undergo oxidative degradation and chain scission. The byproducts are chromophores—conjugated carbonyl and hydroxyl groups—that absorb blue and green light, making the encapsulant appear yellow. The effect is wavelength-dependent: blue LEDs (450–470 nm) suffer more than red LEDs (620–630 nm) because the yellowing absorbs shorter wavelengths more strongly.

Accelerated aging studies on standard 3mm round LEDs with bisphenol-A epoxy domes consistently show the following pattern. At 85°C/85%RH with 20 mA continuous drive:

Table 3: Representative Epoxy Yellowing vs. Time at 85°C/85%RH (Literature Composite)

Hours	Δuv (color shift)	Lumen Maintenance (%)	Visual Assessment
0	0.000	100	Water-clear
500	0.003	96	Slightly hazy
1,000	0.008	89	Noticeable yellowing
2,000	0.018	78	Distinct yellow tint
4,000	0.032	62	Amber appearance
8,000	0.051	44	Deep amber; effectively useless for white/blue

Note: Δuv against CIE 1931 u'v' coordinates. Representative values for a blue LED (470 nm) in a standard 3mm epoxy dome, synthesized from published accelerated aging studies.

The data is unambiguous. After 2,000 hours—roughly three months of continuous operation in a tropical environment—the lumen output has dropped by 22%. For an indicator that started at 500 mcd, that is a drop to 390 mcd. If the design margin was tight, the LED is now below the minimum acceptable brightness threshold.

Mechanism B: Phosphor Thermal Quenching (White LEDs Only)

White LEDs use a blue die with a yellow phosphor coating (typically YAG:Ce). The phosphor conversion efficiency drops as temperature rises—a phenomenon called thermal quenching. At 25°C junction temperature, a typical white LED might convert 25% of blue photons to yellow. At 100°C junction, that conversion efficiency can drop to 18–20%. The result is a bluer, dimmer output even though the die itself is fine.

The fix is thermal management, not better phosphor. Even the best phosphors (silicate-based, nitride-based) still quench. Published comparisons of top-tier phosphors (e.g., Intematix, Merck) show they outperform YAG:Ce by roughly 10–15% at high temperature, but the fundamental physics of non-radiative recombination in the phosphor lattice does not go away. Keep the junction below 85°C and this mechanism largely disappears.

Mechanism C: Die Degradation (Droop and Defect Propagation)

At the semiconductor level, GaN-based blue LEDs suffer from efficiency droop at high current densities and from defect propagation under thermal stress. Threading dislocations in the epitaxial structure act as non-radiative recombination centers. Under forward bias and heat, these dislocations can migrate and multiply, particularly near the p-GaN surface. The result is a gradual reduction in internal quantum efficiency (IQE) that manifests as lumen depreciation.

This is where chip quality matters enormously. A-grade epitaxial wafers from established foundries (Epistar, San'an, OSRAM) have threading dislocation densities below 10^8 cm^{-2} . B-grade and "project" wafers can be 10× higher. The difference in lumen maintenance after 5,000 hours at 85°C can be 15–20 percentage points. Yes, the B-grade chip is cheaper by \$0.005–\$0.01, but the long-term cost is field failures and brand damage.

3.2 Silicone vs. Epoxy: A Decade of Field Data

Around 2012, the high-reliability segment of the LED industry began transitioning from epoxy to silicone encapsulants. The motivation was not sulfuration resistance—it was lumen maintenance. Silicone does not yellow the way epoxy does because the Si-O backbone is far more resistant to oxidative degradation than the C-C backbone of epoxy.

Industry Field Evidence: Epoxy vs. Silicone Long-Term Performance

Published long-term field studies and industry tracking data provide compelling evidence for the lumen maintenance advantage of silicone over epoxy. Independent evaluations of white 5050 SMD LEDs in tropical outdoor signage applications (hot, humid, UV-exposed) have reported lumen maintenance trends consistent with the following pattern:

Table 4: Representative Long-Term Lumen Maintenance — Epoxy vs. Silicone (Literature-Based)

Years in Field	Epoxy Lumen Maintenance	Silicone Lumen Maintenance	Δ (Silicone Advantage)
1	91%	98%	+7%
3	74%	95%	+21%
5	58%	91%	+33%
7	44%	87%	+43%
10	31%	82%	+51%

Note: Data synthesized from published field studies and industry reliability reports on white 5050 SMD LEDs ($\approx 20 \text{ mA}$ per channel) under tropical outdoor conditions. Values are representative of trends reported over multi-year service.

The silicone advantage compounds over time. In these studies, silicone-encapsulated LEDs remained within acceptable lumen maintenance limits even after a decade of service, while epoxy units effectively failed. The BOM-level cost difference between the two encapsulant systems is on the order of a few cents per LED—trivial against the cost of field replacement.

3.3 The Silicone Process Penalty

Silicone is not a free lunch. It has lower adhesion to leadframes than epoxy, which means delamination risk if the surface preparation is inadequate. It also has a higher gas permeability, which worsens sulfuration (as discussed in Chapter 2). And it requires longer cure schedules—typically 1 hour at 150°C versus 30 minutes at 150°C for epoxy. For high-volume SMD lines running at 30k+ units per hour, that extra 30 minutes in the oven is a real capacity constraint.

Process studies have found that plasma cleaning the leadframe before silicone dispensing improves adhesion shear strength dramatically (from single-digit MPa into the high teens)—more than enough for demanding vibration profiles. The plasma step adds only seconds per tray, which is manageable. Without it, delamination failures can appear in thermal shock testing (-40°C to +150°C) that simply do not occur with plasma-treated frames.

CHAPTER 4: CATASTROPHIC DIE FAILURE — OPEN AND SHORT CIRCUITS

4.1 Open Circuit: The Wire Bond Fracture

An open-circuit LED is easy to diagnose: apply forward voltage, measure zero current. The challenge is figuring out *why* the circuit is open. Industry experience suggests that the majority—commonly cited at around 70%—of open-circuit failures in indicator LEDs are due to wire bond fracture. The remainder are split between die cracking, solder joint failure, and leadframe corrosion.

Wire bond fracture almost always occurs at the heel of the wedge or ball bond—the point of maximum stress concentration. Under thermal cycling, the CTE mismatch between the gold wire (14.2 ppm/°C), the die (GaN: ~5.6 ppm/°C), and the leadframe (copper: 17 ppm/°C) creates cyclic shear stress at the bond interface. After enough cycles, a fatigue crack initiates at the heel and propagates across the bond. When the crack reaches the center of the wire, electrical continuity is lost.

Table 5: Representative Wire Bond Fatigue Life by Wire Material and Diameter (Published Data)

Wire Type	Diameter (μm)	Cycles to Failure (-40°C/+125°C)	Failure Mode
Alloy wire, 1N hardness	25	380	Heel crack
Alloy wire, 1N hardness	30	640	Heel crack
Au, 1N hardness	25	420	Heel crack
Au, 1N hardness	30	780	Heel crack
Au, 2N hardness	25	540	Heel crack
Pure Au, 3N hardness	25	650	Heel crack
Pure Au, 3N hardness	20	480	Heel crack

Note: Representative values compiled from published wire-bond reliability studies (GaN die, copper leadframe, ball-wedge configuration, -40°C/+125°C cycling). Failure defined as >20% resistance increase.

Published data makes a strong case for pure gold wire in high-reliability applications: at comparable diameters, 3N-hardness pure gold wire delivers significantly longer fatigue life than 1N gold, and far longer than traditional alloy wire. The trade-offs are the highest material cost and the need for more precise ultrasonic energy and bond-force control with harder wire. For automotive under-hood applications with severe thermal cycling, 3N pure gold wire has become the industry default recommendation; 1N-2N gold wire is the industrial baseline; alloy wire suits only benign consumer environments.

4.2 Short Circuit: Die Migration and EOS

Short-circuit failures are less common than open circuits but often more catastrophic because they can damage the driving circuit. We categorize short-circuit LED failures into three types:

Type 1: Electrostatic Discharge (ESD) Punch-Through. ESD events above the die's reverse breakdown voltage (typically 5–15V for GaN blue LEDs) can create a conductive path through the p-n junction. The damage is often localized to a small melt filament, but the leakage current increases dramatically. In some cases, the LED still emits light at low current but draws excessive reverse leakage—enough to confuse constant-current drivers or drain batteries in portable devices.

Type 2: Electrical Overstress (EOS) from Transients. Inductive kickback from relay coils, motor windings, or long cable runs can generate voltage spikes well above the LED's maximum rating. Unlike ESD, which is nanoseconds in duration, EOS transients can last microseconds to milliseconds, delivering enough energy to melt the die metallization and create a permanent short. We have seen this repeatedly in 24V industrial control circuits where relay suppression diodes were omitted.

Type 3: Ionic Migration (Electrochemical Migration). In the presence of moisture and an electric field, silver ions from the leadframe or die metallization can migrate across the encapsulant surface, forming dendritic bridges between anode and cathode. This is most common in high-humidity environments with poor encapsulant adhesion. The failure is often intermittent at first—resistance fluctuates as the dendrite grows and partially dissolves—before becoming a hard short.

The most insidious of these is ESD latent damage. A die that has suffered a near-threshold ESD event may pass all standard electrical tests—forward voltage, reverse leakage, luminous flux—and still fail within 500 hours of operation. The reason is that the ESD damage creates micro-defects in the active region that act as nucleation points for further defect propagation under normal operating stress. It is like a cracked windshield: the crack is small at first, but every thermal cycle makes it grow.

4.3 ESD Protection: What Actually Works

GaN-based LEDs are inherently ESD-sensitive. Without protection, a typical blue LED has an HBM (Human Body Model) withstand voltage of 500V–1,000V. That sounds adequate until you realize that walking across a carpet in a dry office generates 3,000V–5,000V. In

manufacturing, ESD damage is the leading cause of infant mortality.

There are two practical approaches to ESD protection:

On-chip protection: Most commercial LED dies now include a parallel Zener diode or back-to-back diodes integrated into the die structure. This raises the HBM withstand to 2,000V–4,000V, which is sufficient for most handling scenarios. The downside is a slight increase in die size (5–10%) and a small increase in capacitance, which can matter in high-speed signaling applications. For indicator LEDs, on-chip protection is our strong recommendation.

External TVS diodes: For extremely ESD-sensitive environments or applications where the LED is exposed to user touch (front-panel indicators), an external transient voltage suppression (TVS) diode or series resistor provides additional protection. A 100 Ω series resistor limits ESD current to safe levels for most events, though it also reduces LED brightness and must be accounted for in the driver design.

Best-practice incoming inspection protocols include ESD screening of bare dies before assembly: an ESD simulator applies HBM pulses (e.g., 2,000V) and any die showing excessive post-stress forward voltage shift is rejected. Industry benchmarks for infant mortality in LED assembly, when robust ESD protocols and on-chip protection are implemented, typically range from 50–300 ppm; rigorous screening programs have brought observed rates into the lower end of this range.

CHAPTER 5: FAILURE ANALYSIS METHODOLOGY

When a failed LED arrives at a professional FA laboratory, a systematic protocol preserves evidence and builds a complete picture of the failure chain. The following steps reflect standard industry practice, including our own. Rushing to the microscope is a rookie mistake—you need electrical data first, then destructive analysis.

Step 1: Non-Destructive Electrical Characterization

We start with a full I-V curve from -10V to +10V, measuring forward voltage (V_f) at rated current, reverse leakage (I_r) at -5V, and light output (if any) using an integrating sphere. This tells us whether the failure is open, short, or parametric (dim but functional). We also measure the spectrum to detect phosphor degradation or die shift.

Step 2: X-Ray and CSAM Inspection

Before opening the package, we take X-ray images to check for wire bond integrity, die tilt, and solder voids. We then run C-mode Scanning Acoustic Microscopy (CSAM) to detect delamination at the die-attach or encapsulant-leadframe interfaces. Delamination is often invisible to X-ray but shows up clearly in acoustic images as bright regions where the ultrasound reflects off an air gap.

Step 3: Decapsulation

For epoxy packages, we use a heated mixture of sulfuric acid and nitric acid (3:1) at 120°C to dissolve the encapsulant without attacking the metal structures. For silicone packages,

we use tetramethylammonium hydroxide (TMAH) or mechanical peeling. The goal is to expose the die and wire bonds while preserving any corrosion products or contamination.

Step 4: Microscopic Examination

We examine the exposed die and bonds under a metallurgical microscope (up to 1,000×) and a scanning electron microscope (SEM) if needed. For sulfuration, we look for blackened silver surfaces. For wire bond fractures, we look for heel cracks or neck thinning. For ESD damage, we look for melt filaments or craters in the p-GaN surface. We also perform Energy Dispersive X-ray Spectroscopy (EDX) to identify elemental composition of any foreign material.

Step 5: Cross-Sectioning (if needed)

For die cracking or solder joint failures, we mount the LED in epoxy resin, grind it down to the plane of interest, and polish to a 1µm finish. This reveals internal cracks, voids, and intermetallic compounds that are invisible from the surface. It is time-consuming but often the only way to confirm root cause.

CHAPTER 6: DESIGN AND PROCUREMENT BEST PRACTICES

6.1 The Procurement Checklist

Most LED failures are preventable at the procurement stage. Here is the checklist our application engineering team recommends when qualifying a new LED supplier or part number:

- ☐ **Request the die source and grade.** A-grade epi from a known foundry? Or B-grade/project material with unknown provenance? If the supplier will not tell you, that is a red flag.
- ☐ **Verify ESD protection level.** HBM 2,000V minimum for handling robustness. MM (Machine Model) 200V if the LED will be assembled on automated equipment.
- ☐ **Check encapsulant type.** Epoxy for cost-sensitive, short-life consumer apps. Silicone for industrial, outdoor, or any application requiring >5,000 hours.
- ☐ **Confirm leadframe plating.** Ag-plated is standard but risky in sulfur environments. Ask about PPA, EMC, or Au/Pd alternatives if the application environment is unknown.
- ☐ **Review wire bond material.** Gold wire is fine for benign environments. Specify gold wire for automotive or severe thermal cycling. Avoid copper or aluminum wire for high-humidity applications due to corrosion risk.
- ☐ **Demand reliability data.** At minimum: 1,000 hours HTOL at maximum rated temperature, 500 cycles TCT -40°C/+125°C, and 168 hours HAST at 130°C/85%RH.
- ☐ **Audit the factory.** ISO 9001 is table stakes. For automotive, IATF 16949 is mandatory. Look at the wire bonder maintenance logs, the die attach cure ovens, and the ESD protection at each station.

6.2 Circuit Design Considerations

Even the best LED can be killed by a bad driver circuit. Here are the most common design errors we see:

Error 1: Driving LEDs with constant voltage instead of constant current. LEDs have a negative temperature coefficient of forward voltage (-2 to -4 mV/°C). If you drive from a voltage source, a small temperature rise causes a small V_f drop, which causes a large current increase, which causes more heating—a thermal runaway. Always use a constant-current source or at least a series resistor sized for worst-case temperature.

Error 2: Omitting reverse polarity protection. GaN LEDs have low reverse breakdown voltage. A brief reverse voltage spike from an inductive load can destroy the junction. A simple Schottky diode in parallel (reverse-biased) or a series diode provides cheap insurance.

Error 3: Ignoring inrush current. When a cold LED is first powered, the initial current surge can exceed steady-state by 2–3× for a few milliseconds. With PWM dimming at high frequency, this happens repeatedly. A small capacitor (10–100 nF) across the LED or a soft-start driver mitigates this.

Error 4: Insufficient derating. The datasheet maximum ratings are not design targets. For industrial applications, we recommend operating at 70% of maximum continuous current and keeping junction temperature below 80% of maximum rated T_j . This provides margin for ambient temperature excursions and component aging.

CHAPTER 7: CASE STUDIES FROM THE FIELD

The following case studies are composite scenarios based on common failure patterns observed in the industry. They are provided for educational and illustrative purposes and do not represent specific customer engagements.

Case Study 1: The Paper Mill PLC Panel

Application: Status indicators on PLCs in a high-sulfur industrial environment (pulp & paper sector). **Failure:** LEDs exhibited reflector blackening within 6–12 months of installation. **Root Cause:** Elevated H_2S levels in control cabinets due to poor ventilation and sulfur-cured cable gaskets, combined with standard Ag-plated 3mm LEDs with epoxy domes. **Solution:** Transition to PPA-reflector LEDs with silicone encapsulant; activated carbon breathers on the enclosure; peroxide-cured silicone gaskets. **Result:** Elimination of sulfuration failures in follow-up evaluations; lumen maintenance consistent with silicone performance expectations.

Case Study 2: The EV Charging Station Display

Application: 7-segment display and status LEDs in outdoor EV charging stations in a hot desert climate. **Failure:** Segment brightness dropped noticeably (around 40%) within 18 months; some segments went open-circuit. **Root Cause:** Excessive junction temperatures during summer afternoons due to inadequate heat sinking. Epoxy encapsulant yellowing

combined with alloy wire bond heel cracks from thermal cycling. **Solution:** Redesigned PCB with thermal vias under each LED, switched to silicone encapsulant, upgraded to 25µm 3N pure gold wire bonds, and added a current derating curve that reduces drive current above 60°C ambient. **Result:** Junction temperature reduced to a safe level. Lumen maintenance returned to expected silicone performance, with no further open-circuit failures in follow-up.

Case Study 3: The Medical Device Infant Mortality Spike

Application: Front-panel indicators on portable patient monitors. **Failure:** Field failure rate above 3% within the first 200 hours—far above the ppm-level target. **Root Cause:** ESD damage during final assembly. The contract manufacturer had removed ESD wrist strap stations to increase throughput, and dies without on-chip Zener protection were damaged by high-voltage HBM events during manual insertion. **Solution:** Mandated on-chip ESD protection (HBM 4,000V class) for all LEDs; restored ESD protocols at the contract manufacturer; added 100% ESD pre-screening at incoming inspection. **Result:** Field failure rate dropped back to normal ppm levels. The minor per-unit cost increase for protected dies was trivial compared to the warranty and recall costs.

APPENDIX: TEST STANDARDS AND CONDITIONS

The following standards and test conditions are referenced throughout this whitepaper:

- **JEDEC JESD22-A108:** Temperature, Bias, and Operating Life (HTOL)
- **JEDEC JESD22-A104:** Temperature Cycling (TCT)
- **JEDEC JESD22-A110:** Highly Accelerated Temperature and Humidity Stress Test (HAST)
- **JEDEC JESD22-A101:** Steady-State Temperature Humidity Bias Life Test (85°C/85%RH)
- **ANSI/ESDA/JEDEC JS-001:** Electrostatic Discharge Sensitivity Testing (HBM)
- **IES LM-80-20:** Measuring Lumen Maintenance of LED Packages, Arrays, and Modules
- **IES TM-21-11:** Projecting Long Term Lumen Maintenance of LED Light Sources

For questions, technical consultations, or sample requests, contact the Hongcheng Application Engineering team: sales@led-hc.com & +86 139 2571 4318.