Ambient lighting design utilizing RGB LEDs

Application Note

Published by ams-OSRAM AG
Tobelbader Strasse 30,
8141 Premstaetten Austria
Phone +43 3136 500-0
ams-osram.com

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Application Note No. AN117

Valid for:
MULTILED® (LRTB GVSG)

Abstract

MULTILED RGB LEDs offer flexible solutions for tunable color applications in automotive interior lighting.

This application note describes the advantages and challenges of utilizing RGB LEDs. Besides pointing out practical challenges, preferred solutions for RGB LEDs are outlined and discussed to assist customers with engineering design solutions.

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1 Advantages of RGB LEDs

Color tunable ambient lighting functions enhance customer comfort and user experience. The large color gamut that is feasible with RGB LEDs provides a lot of room for individualization based on the user preference and also allows to match certain light functions e.g. to user biometrics or device infotainment.

The applications for RGB LEDs differ from classical single-color LEDs. RGB LEDs have significant benefits when it comes to tunable and/or multi-color applications. However, color control with RGB LEDs does come with its challenges. LED variation, temperature shifts, and driver noise make color consistency a challenging topic. These issues will be discussed in this application note followed by optimized technical solutions for RGB ambient lighting.

While an RGB LED can be used to create white light, it should not be mistaken for an ideal light source for artificial illumination. The color rendering index (CRI) describes a light sources ability to render an objects color compared to a reference light source. While phosphor-based white LEDs have CRI values between 70 and 90, the CRI of RGB LEDs is < 50. This is due to the lack of an RGB LED's of spectral content in cyan, yellow and orange, as observable in Figure 1. Thus for illumination applications, high CRI white LEDs are recommended. An overview of the major differences between both LED types is given in Table 1.

Figure 1: Spectral emission profile of an RGB LED and the sun

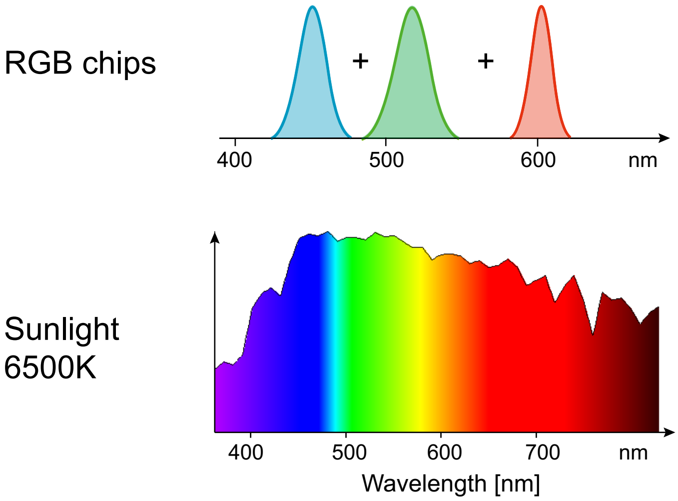


Table 1: Major differences between RGB and white LEDs

RGB LED	White LED
One package combining chips of 3 different colors (red, green, blue)	Package with one chip (blue) and a convertor (yellow)
Multi-color capacity	Single-color
Tunable color	White color
Low CRI	High CRI
Challenging color control	Non-tunable output color

2 RGB LED design

RGB LEDs are available in many form factors suitable for a large variety of applications. For example Multi CHIPLED® LEDs are used in applications requiring a small footprint, DISPLIX® LEDs are utilized in outdoor video walls and OSRAM OSTAR® Stage are incorporated for architectural and stage lighting.

The MULTILED® LED, shown in Figure 2, is the standard RGB package and contains three independent chips assembled into one package.

Figure 2: MULTILED®

InGaAlP for Red:	620 - 632 nm
InGaN for True Green:	519 - 546 nm
InGaN for Blue:	447 - 476 nm

3 Challenges in driving RGB LEDs

Most RGB LEDs have 6 pads to connect the cathode and the anode of each LED chip, allowing each die to be driven independently from one another. The output results in an additive mixture of ocular stimuli to achieve a desired final color. Controlling the color of RGB LEDs comes with its challenges, as variation in the chip, together with other influencing factors including temperature shifts have a major impact on the color point of the LED.

Most multi-color LEDs from ams-OSRAM are binned for both color and intensity of each chip in the package. A standard RGB MULTILED will have 6 binning categories. Since there is inherent variation between individual LED dies during production, brightness binning significantly reduces the variation of the optical characteristics of the LEDs within a single reel. Additionally, wavelength binning for RGB LEDs is done to assist customers with achieving a specific gamut.

This application note discusses in detail the major challenges (listed below) for achieving a stable color point and delivers solutions to overcome them.

- Temperature drifts
- Current fluctuations
- Binning size
- Lifetime degradation

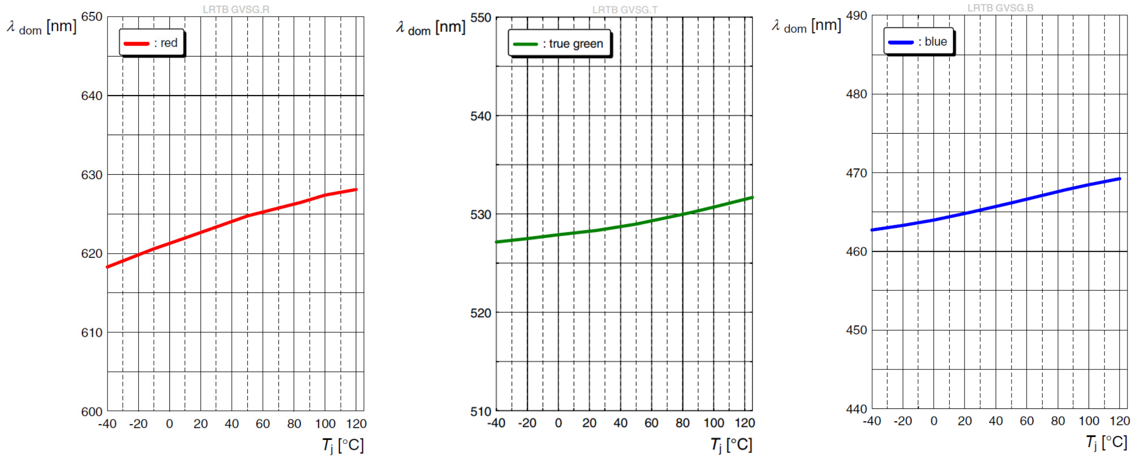
3.1 Temperature drifts

Temperature variations have an impact on the spectrum of the LED. Therefore, the temperature dependence of the LED parameters are evaluated in the temperature range from -40 °C to +120 °C (T_J).

For the LED chips, an increase in temperature leads to an expansion of the crystal lattice. This results in an increase in the lattice constant and a smaller band gap energy. The band gap energy has an inverse correlation with the emission wavelength of the semiconductor material. Thus, an increase in temperature results in a shift towards a longer emission wavelength and a reduced forward voltage V_F. Figure 3 shows the data sheet curves for the dominant wavelength for all colors. As the temperature of the LED increases, the dominant emission wavelength for all three dies increases.

This effect needs to be taken into account in a color correction algorithm in order to achieve good color accuracy.

Figure 3: Dominant wavelength versus temperature of the MULTILED® LRTB GVSG LED (I_F = 20 mA)



The blue and green spectra shift into the region of increased eye sensitivity, whereas the red spectrum shifts towards decreased luminous eye sensitivity (Figure 4). This effect contributes to the overall behavior of intensity versus temperature. The other effect is the reduced electron hole recombination with increasing temperature.

Figure 4: Dominat wavelength shifts in relation to increasing LED temperature

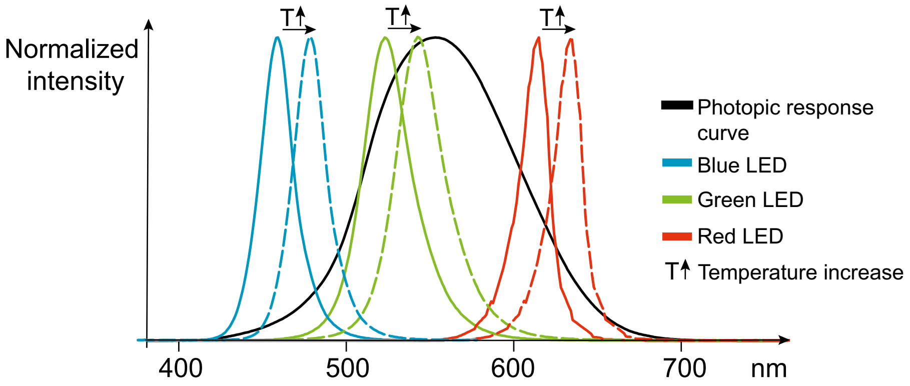
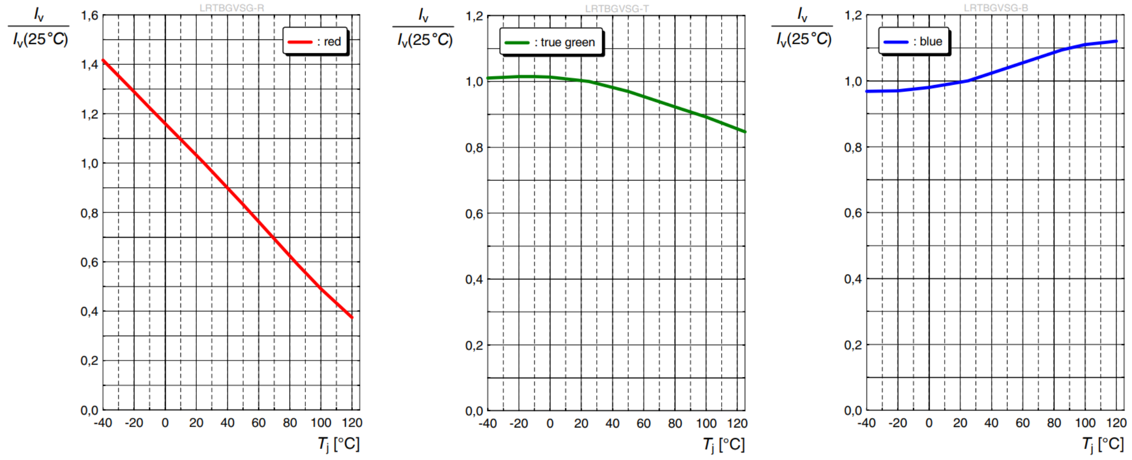


Figure 5 shows the intensity versus temperature behavior for all three chips used in the LRTB GVSG LED. The luminous intensity of red InGaAlP LEDs significantly decreases with increasing LED operating temperatures. For blue and green InGaN LEDs the decrease in luminous intensity is less pronounced. If the application shows a temperature gradient between the LEDs, this can result in visible color variations.

For temperature control, it is recommended to monitor the temperature of the LED solder joint. Temperature information can be utilized to compensate for shifts in LED parameters and correctly hit desired color targets. Please refer to the chapter 4 "Solutions for color control" for a detailed description.

Figure 5: Relative luminous intensity $I_V/I_V(25\ °C) = f\ (T_J)$, $I_F = 20$ mA

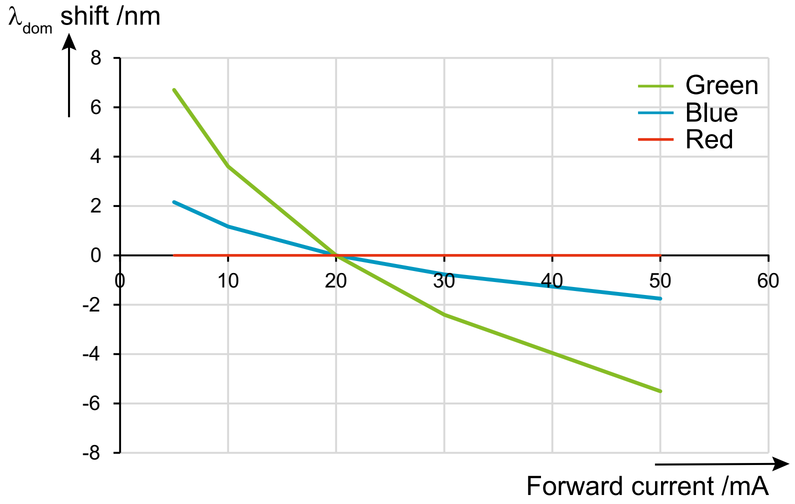


3.2 Current fluctuations

Forward current plays an additional role in color consistency. LEDs do not follow a perfectly linear relationship between forward current and luminous intensity, an effect called LED droop. The details on the curves can be found in the data sheet.

In addition there is also a dependency of the dominant wavelength of the LED chip on the forward current. Figure 6 shows the details for different colors. For red there is hardly any color shift as a function of current, whereas blue and green show a reduction of the dominant wavelength with increasing forward current. Green shows a larger effect than blue. Taking these current density effects into account is very complex and therefore it is recommended to drive each LED chip with a constant current source and using pulse width modulation (PWM) to adjust the individual brightness of each chip. This approach will result in better color control. Please refer to the chapter 4 "Solutions for color control" for a detailed explanation.

Figure 6: Wavelength change per LED die as a function of forward current

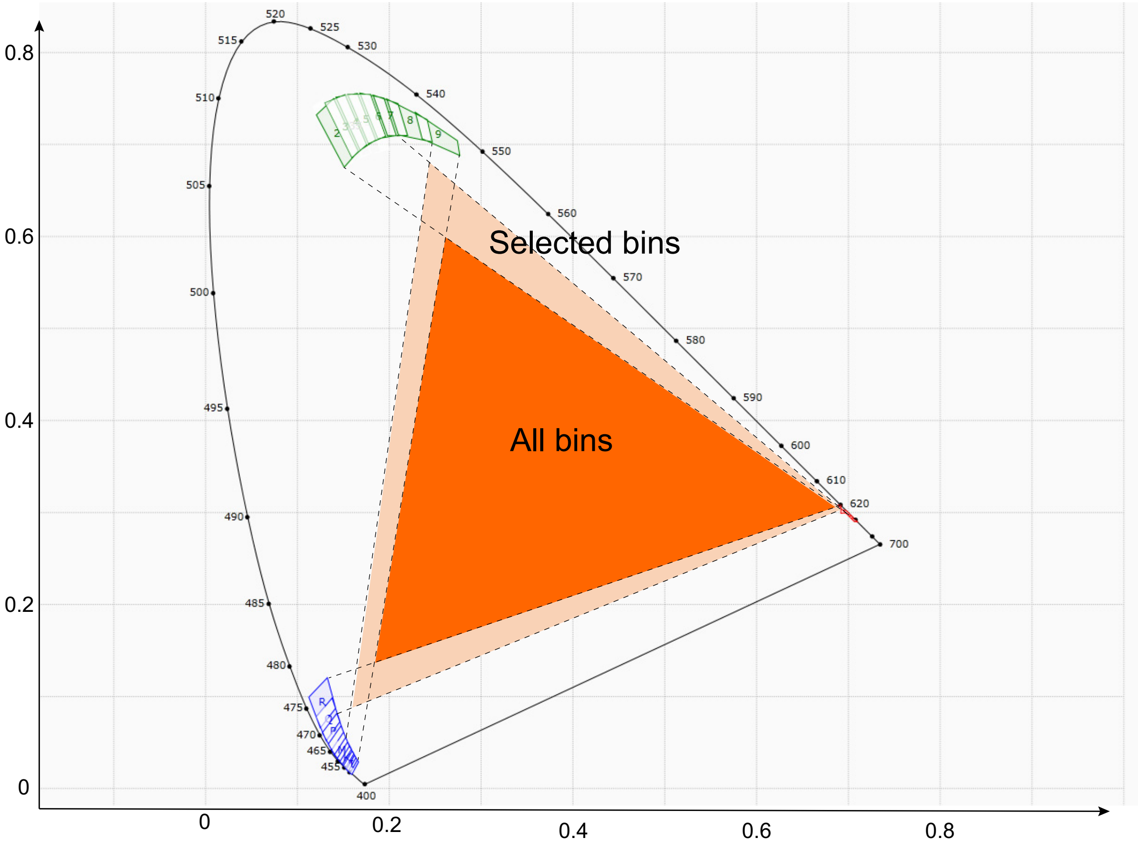


3.3 Binning size

The color and intensity of all three dies in the RGB package determine the achievable color of the LED. The range of colors available in a system is called color gamut.

Tight chromaticity binning enables customers to improve the overall color gamut of their system. The number of selected color bins influences the size of the common color gamut achievable with that LED binning group. This is illustrated in Figure 7, where a small selection of color bins allows for more saturated color options and a larger gamut than in the case of all the color bins combined. Tight binning also ensures that products can attain desired color target points, particularly those set by the end customer to maintain color homogeneity.

Figure 7: Color gamut size as a function of color bin selection

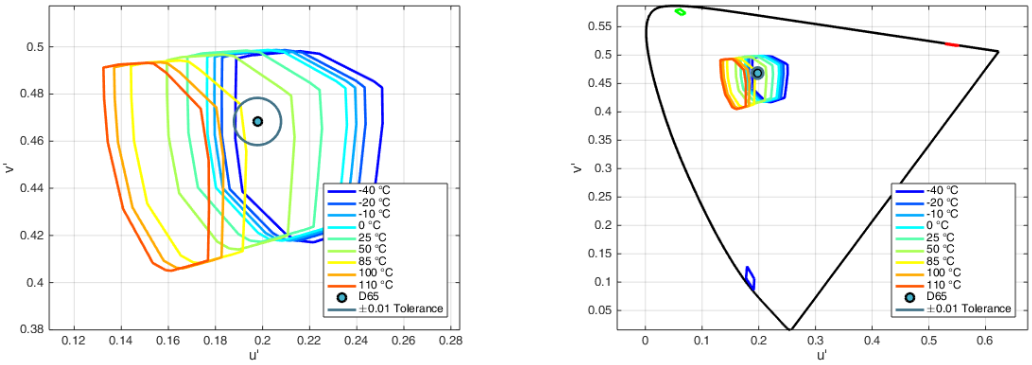


To improve color consistency, ams-OSRAM provides extremely tight intensity and color binning. For example the MULTILED LRTB GVSG has 22 color bins and 31 intensity bins. Each reel that is delivered will have only one color bin and one intensity bin for each die in the RGB LED. While binning significantly reduces possible color distribution, it does not remove color inconsistencies completely. Figure 8 shows that an RGB LED without temperature control will not consistently hit the desired color target, even for single color and brightness bins. Thus, tightening manufacturing tolerances alone will not improve the color precision of RGB LEDs.

3.4 Single bin versus calibration

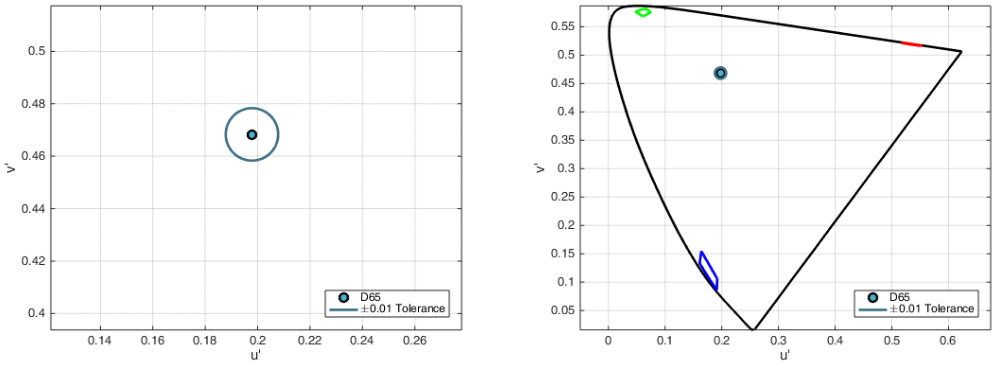
The target for RGB ambient lighting is to achieve color stability within the defined color gamut with an accuracy of typically ± 0.01 (u´v´) under all operating conditions. This includes the full temperature range and lifetime of the LED. The color point variation for a single color and brightness bin is shown in Figure 8. This Figure shows that RGB LEDs must be calibrated and corrected with temperature compensation, even for single color and brightness bins.

Figure 8: Color point and distribution for a single color and brightness bin, but without calibration and temperature control



With calibration, target points can be accurately obtained, as shown in Figure 9. Calibration also allows the use of multiple intensity and color bins without any reduction of color accuracy, assuming that the desired targets are within the bin selection´s color gamut.

Figure 9: Calibrated module with temperature compensation



Used Bins:

	Red	Green	Blue
I_v	UI, UJ, VC, VD	AM, AN, AO, AP	TC, TD, TE, TF
Color	2, 3	4, 5, 6	M, N, O

3.5 Lifetime degradation

An LEDs performance diminishes over time due to environment and aging. Although ams-OSRAM recommends specific operating conditions to maximize LED lifetime, LED output degradation over continued use is a natural process. While the gradual dimming of one die is quite tolerable for single color LEDs, the effects are compounded in RGB LEDs.

Package aging is a factor that needs to be considered for color accurate RGB LED applications. It is mainly driven by the reduction in reflectivity (“also known as browning”) of the LED cavity material. This aging effect is mainly caused by high operating temperatures in combination with high levels of short wavelength (blue light) irradiation. For more details on aging please refer to the application note "Reliability and lifetime of LEDs".

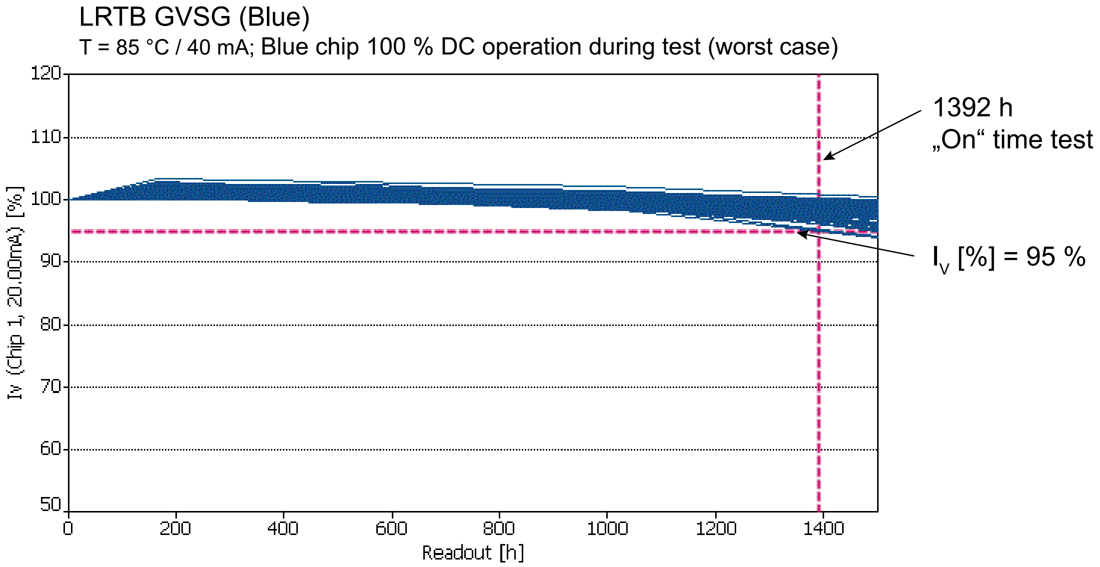
For an RGB LED, package aging will start in the vicinity of the blue LED die. Therefore, the blue intensity will decrease first while red and green will decrease more slowly over a longer time period. In order to estimate the effect of package aging it is important to take an exemplary mission profile of the application into account. Table 3 shows an exemplary mission profile that is relevant for an automotive interior RGB application. This mission profile can be converted into equivalent operating hours under reliability test conditions. In this example, the test conditions $T_{A\ test}$= 85 °C and $I_{F\ test}$= 40 mA are applied, which result in $T_{J\ test}$= 132 °C. The corresponding models used for this conversion are based on the Arrhenius model.

Table 2: Exemplary mission profile

Profile	$T_{Ambient}$	T_{LED} [T_J]	"On" time profile	AF	"On" time test
6 %	- 40 °C	1 °C	480 h	465.84	1 h
20 %	23 °C	64 °C	1600 h	13.21	121 h
65 %	40 °C	81 °C	5200 h	6.28	829 h
8 %	75 °C	116 °C	640 h	1.66	385 h
1 %	80 °C	121 °C	80 h	1.40	57 h
			8000 h		1392 h

For this mission profile, the 8,000 hours lifetime corresponds to ~ 1,400 hours under reliability test conditions (85 °C ambient temperature @ 40 mA driving current for blue). The intensity reduction for blue is the best indicator for package degradation and will be used for a worst case assessment of package aging. The reliability test results, which are shown in Figure 10, serves as an example for the package aging process. The intensity distribution after 1400 hours ranges between 95 % and 100 % of the initial brightness with an average intensity degradation of about 2.5 % which will not be visible to the eye. On the other hand the eye is very sensitive to color differences and therefore color accuracy is a much better indicator when considering package aging effects for RGB applications.

Figure 10: Lifetime degradation of the LRTB GVSG for the blue chip exemplary



Typical color accuracy requirements for an RGB applications are ± 0.01 in u’v’. For a worst case estimate on package aging, we assume a 5 % reduction in the blue intensity and no intensity reduction in the red and green. Of course if the intensity of all colors would decrease at the same rate there would be no impact in color but just on intensity. Targeting a typical white point leads to a maximum color difference of 0.003 (u’v’) between the two extreme LEDs (95 % versus 100 % intensity) which is well below the requirement of 0.01. Additionally, in a real world application, the blue LED die will not always be driven constantly at full power over the whole lifetime. From the data above it can be clearly concluded that for an automotive interior application based on the LRTB GVSG it is not necessary to take package aging into account and feed it into a compensation algorithm.

4 Solutions for color control

Methods to control both LED color and intensity must be implemented to overcome the numerous challenges previously described in RGB LED systems. The main reasons for variation in color output of RGB LEDs are variations of intensity and wavelength within the individual bins and forward current and temperature dependencies.

For good color control of the RGB LEDs the following points have to be considered:

- Calibration
- Temperature stabilization
- Thermal management

4.1 Calibration

Many RGB modules can undergo a calibration procedure to maximize LED color and brightness consistency. Either populated on an open PCB, or integrated into the final product, the module is pre-programmed with the LED’s initial properties. During normal operation, the module utilizes this stored information and adjusts the driving conditions based on temperature measurement to hit the desired color and intensity target.

Application specific integrated circuits (ASICs) are available in many form factors and are integrated with a microprocessor, constant current controllers and on-board memory. They can be passively (generic) calibrated with the RGB LED’s performance information, including wavelength and intensity from prior measurements. In order to achieve good color accuracy, active calibration with the measured LED parameters on PCB, at the default driving conditions, needs to be incorporated. While requiring a more complex production setup, active calibration does not require prior LED performance information. Calibration improves the module´s color accuracy, and allows for a more relaxed LED binning selection (see Figure 9).

4.2 Color and brightness stabilization over temperature

RGB LEDs must be electrically driven by using a constant current source and the LED´s luminous intensity should be controlled through pulse width modulation (PWM). An on-board thermistor is required to measure the local temperature of the LED. This information is used by the microprocessor´s algorithm to adjust the PWM duty cycles to compensate for shifts in the LED´s wavelength and intensity. For detailed information on PWM please refer to the application note “Dimming InGaN LEDs”.

The location of the thermistor is important in accurately determining real-time thermal conditions of the RGB LED. With the red die being the most sensitive to temperature changes, it is recommended to place the thermistor near the red anode’s footpad of the RGB LED. Some ASICs have a thermistor conveniently packaged inside the component to minimize design footprint requirements.

4.3 Thermal management

Thermal management is important to stabilize the LED´s output. The LED´s p-n junction temperature (T_J) represents one of the major factors which influence the lifetime and the reliability of LEDs. Lower the junction temperatures result in higher expected lifetimes. The maximum allowed value for T_J can be found in the product data sheet. Detailed information on this topic is provided in the application notes “Package related thermal resistance of LEDs” and “The thermal measurement point of LEDs”.

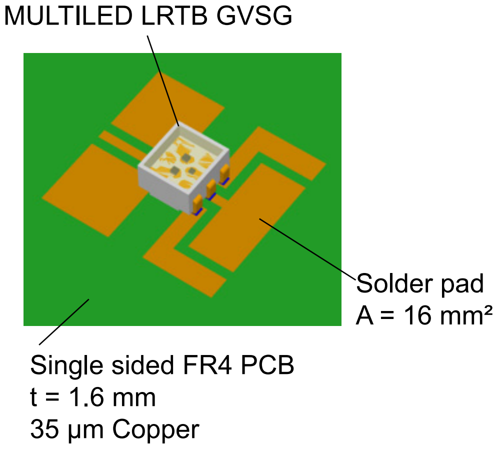
Determining the junction temperature of RGB LEDs is challenging because the direct thermal measurement of the p-n junction is almost impossible. The measurement point and estimated junction temperature depend on the RGB LEDs mode of operation. In general, the junction temperature can be theoretically calculated from the LED´s thermal resistance and temperature readings from thermocouples placed as temperature sensors on the LEDs solder joints.

Since RGB LEDs operate over various modes, only simulated examples for T_J can be given. These simulations can be used either as a starting point or as an initial guide. However, the junction temperature is dependent on the boundary conditions, which have to be determined by the customer.

An exemplary thermal simulation of the LRTB GVSG LED is provided to illustrate the procedure in determining the LED's junction temperature. The simulation model and boundary conditions for this example are shown in Figure 11. Thermal simulations were performed to show the dependency of the junction temperature on the driving conditions of the LED. The simulation was performed for a common white point (C_x, C_y = 0.31), as shown in Figure 12 as well as for driving all three dies at a current of 20 mA, as shown in Figure 13.

Figure 11: Boundary conditions of the thermal simulation of the junction temperatures T_J

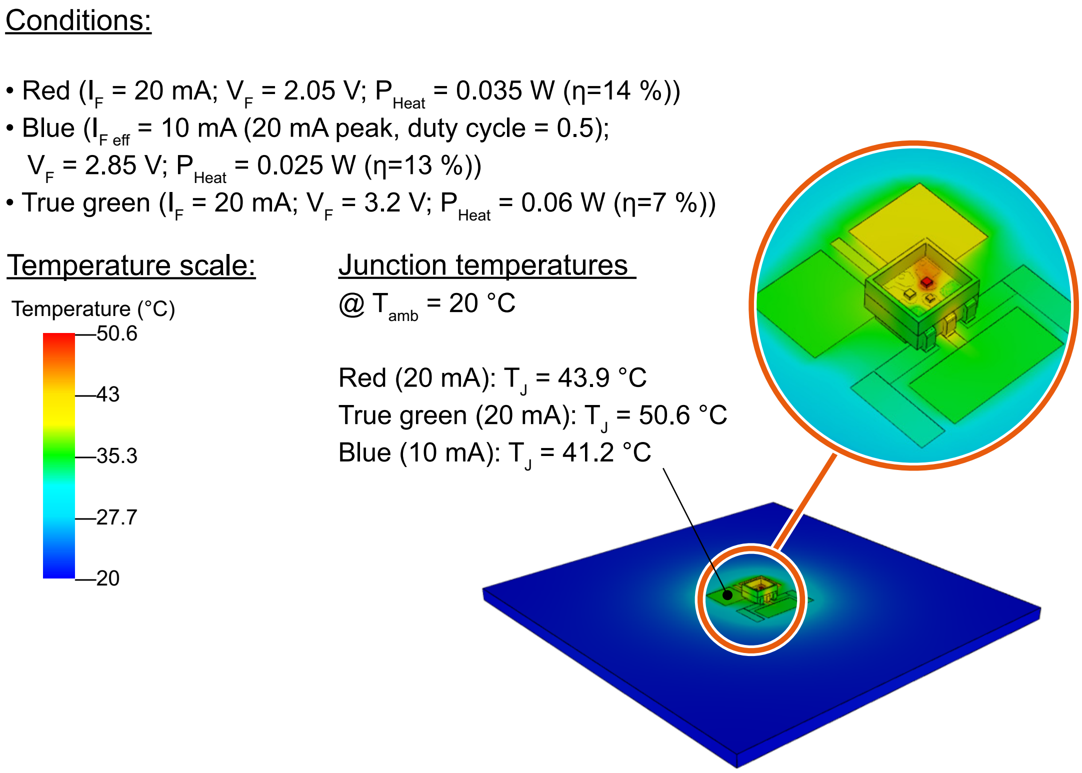
Simulation model:



Boundary conditions:

- Ambient temperature T_{amb} = 20 °C
- Still air
- Conjugate heat transfer
- Steady state solution
- Conjugate heat transfer

Figure 12: Thermal simulations of white point (C_x = 0.32/ C_y = 0.33)



Conditions:

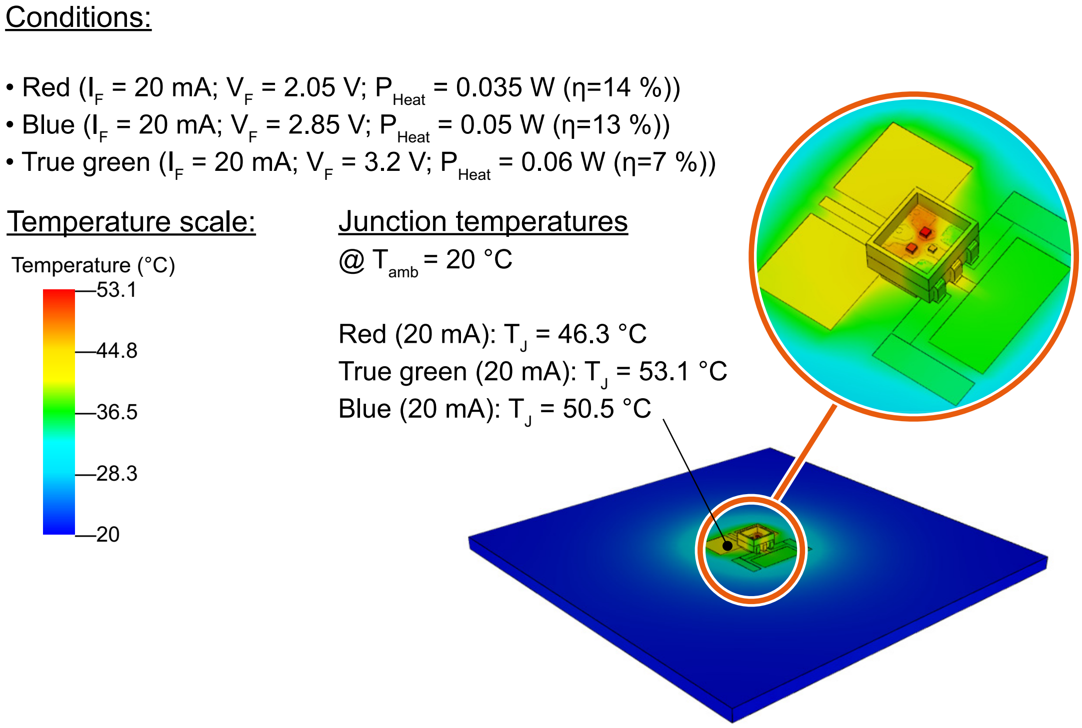
- Red (I_F = 20 mA; V_F = 2.05 V; P_{Heat} = 0.035 W (η=14 %))
- Blue ($I_{F\ eff}$ = 10 mA (20 mA peak, duty cycle = 0.5); V_F = 2.85 V; P_{Heat} = 0.025 W (η=13 %))
- True green (I_F = 20 mA; V_F = 3.2 V; P_{Heat} = 0.06 W (η=7 %))

Temperature scale:

Junction temperatures @ T_{amb} = 20 °C

Red (20 mA): T_J = 43.9 °C
True green (20 mA): T_J = 50.6 °C
Blue (10 mA): T_J = 41.2 °C

Figure 13: Thermal simulation of all chips operated at 20 mA



Conditions:

- Red (I_F = 20 mA; V_F = 2.05 V; P_{Heat} = 0.035 W (η=14 %))
- Blue (I_F = 20 mA; V_F = 2.85 V; P_{Heat} = 0.05 W (η=13 %))
- True green (I_F = 20 mA; V_F = 3.2 V; P_{Heat} = 0.06 W (η=7 %))

Temperature scale:

Junction temperatures @ T_{amb} = 20 °C

Red (20 mA): T_J = 46.3 °C
True green (20 mA): T_J = 53.1 °C
Blue (20 mA): T_J = 50.5 °C

Based on these thermal simulations the junction temperatures of each chip depend on the driving current for each die under the same boundary conditions. Thus, a careful evaluation of the thermal setup is crucial to predict the LED´s junction temperature.

5 Example for color mixing

This is a step-by-step guide to determine the PWM duty cycles (x) required for a measured RGB LED (A) to achieve a specified color target (T).

1. Take an optical measurement of the RGB LED for both brightness and color points for each of the individual dies. Each die (i = R, G, B) will exhibit a luminous intensity (I_i) and a CIE color point (C_{xi}, C_{yi}).

2. Build the Tristimulus matrix (A) of the input RGB LED values.

$$A = \begin{bmatrix} X_R & X_G & X_B \\ Y_R & Y_G & Y_B \\ Z_R & Z_G & Z_B \end{bmatrix}$$

, with $Y_i = I_i$, $X_i = Y_i \cdot \frac{C_{xi}}{C_{yi}}$ and $Z_i = Y_i \cdot \frac{1 - C_{xi} - C_{yi}}{C_{yi}}$

Tristimulus values need to be adjusted as a function of the temperature based on the curves of the data sheet.

3. Set the color target T (in Tristimulus values) inside the gamut of the RGB LED’s

$$T = \begin{bmatrix} T_X \\ T_Y \\ T_Z \end{bmatrix}$$

, with $Y_i = I_i$, $X_i = Y_i \cdot \frac{C_{xi}}{C_{yi}}$ and $Z_i = Y_i \cdot \frac{1 - C_{xi} - C_{yi}}{C_{yi}}$

4. Allow x to be the PWM duty cycles required to reach the target.

$$x = \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

5. Solve the linear equation by inverse matrix or determinant calculations:

$$A \cdot x = T \rightarrow x = A^{-1}T$$

$$R = \frac{det(A1)}{det(A)} = \frac{det\begin{bmatrix} T_X & X_G & X_B \\ T_Y & Y_G & Y_B \\ T_Z & Z_G & Z_B \end{bmatrix}}{det\begin{bmatrix} X_R & X_G & X_B \\ Y_R & Y_G & Y_B \\ Z_R & Z_G & Z_B \end{bmatrix}}$$

$$G = \frac{det(A2)}{det(A)} = \frac{det\begin{bmatrix} X_R & T_X & X_B \\ Y_R & T_Y & Y_B \\ Z_R & T_Z & Z_B \end{bmatrix}}{det\begin{bmatrix} X_R & X_G & X_B \\ Y_R & Y_G & Y_B \\ Z_R & Z_G & Z_B \end{bmatrix}}$$

$$B = \frac{det(A3)}{det(A)} = \frac{det\begin{bmatrix} X_R & X_G & T_X \\ Y_R & Y_G & T_Y \\ Z_R & Z_G & T_Z \end{bmatrix}}{det\begin{bmatrix} X_R & X_G & X_B \\ Y_R & Y_G & Y_B \\ Z_R & Z_G & Z_B \end{bmatrix}}$$

The determinant of a 3x3 matrix can be calculated using the following equation:

$$det\begin{bmatrix} a11 & a12 & a13 \\ a21 & a22 & a23 \\ a31 & a32 & a33 \end{bmatrix} = a11 \cdot a22 \cdot a33 + a12 \cdot a23 \cdot a31 + a13 \cdot a21 \cdot a32 - (a12 \cdot a21 \cdot a33) - (a13 \cdot a22 \cdot a31) - (a23 \cdot a32 \cdot a11)$$

6 Summary

RGB LEDs enable ambient light solutions that offer very large color gamut as well as color tunability. The challenges of tight color control over all operating conditions can be overcome by using suitable connective algorithms and LED driving schemes.

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