

## Comparison of simple LED circuits for low power LEDs

### Application Note



**Valid for:**  
visible LEDs; Infrared Emitters

### Abstract

Light emitting diodes (LEDs) are used in a broad array of applications such as cars, mobile devices, medical applications and illumination. To combine more LEDs in an application is not uncommon. In general, operation with a constant power source (or with a LED driver) is recommended. For low power LEDs sometimes more cost-efficient implementations are chosen. Hence this application note compares different LED circuits, explains the advantages, gives examples and recommendations.

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## Table of contents

A. Basic electrical LED information .....	2
Electrical characteristics of the LED .....	2
Forward voltage grouping .....	3
B. LED circuits .....	4
Simulation parameters .....	5
Circuit topology 1: serial circuit .....	5
Circuit topology 2: matrix circuit .....	7
Advantages and disadvantages of the different circuit topologies .....	9
LED circuits recommendation .....	10
C. Thermal considerations .....	12
D. Conclusion .....	12

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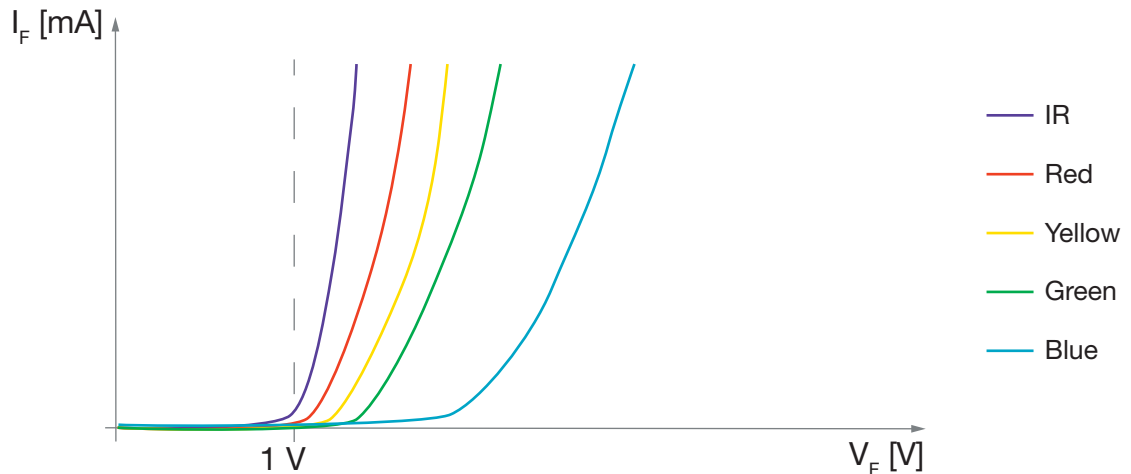
## A. Basic electrical LED information

### Electrical characteristics of the LED

LEDs are optoelectronic semiconductors with an pn-junction that converts electrical energy into light when forward voltage is applied. The color of the light depends on the semiconductor materials used. The characteristics of the LED forward voltage have the following properties:

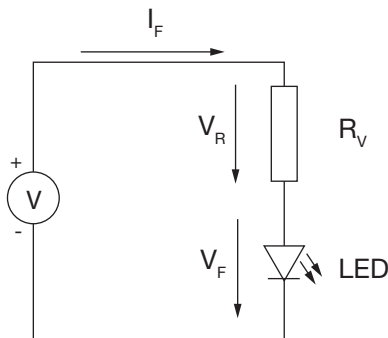
- A forward voltage threshold must be reached before the diode will start conducting
- LEDs show a negative temperature coefficient (NTC) behavior
- The LED is non-conductive in reverse
- LEDs have a nonlinear I-V characteristic (Figure 1)

Figure 1: Sketched example for LEDs nonlinear I-V characteristic



LEDs are very sensitive to a high forward current. Therefore, an LED should never be connected directly to the supply voltage. They should always be connected in series within a current controlled or current limited circuit. Figure 2 shows an example of a simple basic circuit.

Figure 2: Example of a simple basic circuit with a LED



### Forward voltage grouping

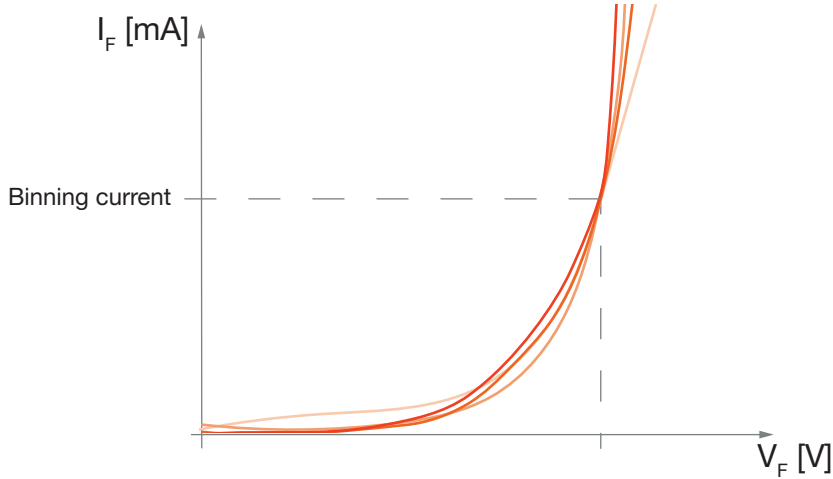
In order to meet the required standards of light-output it may be necessary to segregate the forward voltage of the LEDs into groups (binning). Most LEDs are usually binned at a certain grouping current. The binning always refers to a certain junction temperature of the chip. By tightly controlling the parameter of voltage in such a way, a better uniformity in appearance is achieved in the end application.

The list below shows exemplary the voltage groups and values of the Power TOPLED® LA E6xF:

- 3A:  $V_f = 1.90 \text{ V} - 2.05 \text{ V}$ , ( $V_{f \text{ typ}} = 1.975 \text{ V}$ )
- 3B:  $V_f = 2.05 \text{ V} - 2.20 \text{ V}$ , ( $V_{f \text{ typ}} = 2.125 \text{ V}$ )
- 4A:  $V_f = 2.20 \text{ V} - 2.35 \text{ V}$ , ( $V_{f \text{ typ}} = 2.275 \text{ V}$ )
- 4B:  $V_f = 2.35 \text{ V} - 2.50 \text{ V}$ , ( $V_{f \text{ typ}} = 2.425 \text{ V}$ )

But even LEDs with identical binning values can have different I-V characteristics. Figure 3 shows an example with a binning current of 150 mA. As can be seen, all three LEDs have the identical binning values, but show a different I-V characteristic.

Figure 3: Sketched example same binning values but different I-V characteristic

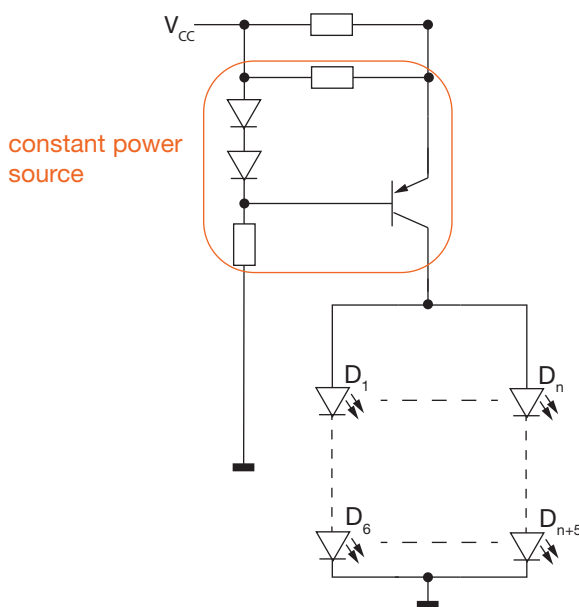


## B. LED circuits

There are different possibilities to operate LEDs in applications.

It is recommended to operate LEDs with constant current and pulse width modulation (PWM), as shown in Figure 4. Constant power sources ensure a constant operating current at a defined operating point. LED drivers offer the constant power source as an integrated solution. For more information on operating LEDs with pulse width modulation (PWM), please refer to Application Note: “[Dimming InGaN LEDs](#)”.

Figure 4: LED circuit with constant power source



In practice, for low-cost applications and using low power LEDs, circuits without a constant power source are often implemented. In the following two circuit topologies are presented:

- Circuit topology 1: Serial Circuit with different LED strings in parallel
- Circuit topology 2: Matrix Circuit with one resistor for the complete circuit

To demonstrate LED performance in a circuit, for each topology two simulations have been performed:

- a typical simulation with all LEDs performing normally
- a simulation with one failed LED in the circuit from a string with typical forward voltage

### Simulation parameters

For each circuit simulation constant proceeding parameters are considered:

1. Sixteen Power TOPLED® (LA E6xF) LEDs with a voltage group 3B ( $V_f = 2.125 \text{ V @ } 50 \text{ mA}$ ) have been used, wherein four strings are arranged in series and of those four LEDs are in parallel.
2. The LED strings for each circuit have been arranged from left to right in a minimum, typical (definition: mid), maximum arrangement of forward voltage. This equates to the following forward voltages:
  - left most string:  $2.05 \text{ V @ } 50 \text{ mA}$
  - middle two strings:  $2.125 \text{ V @ } 50 \text{ mA}$
  - right most string:  $2.20 \text{ V @ } 50 \text{ mA}$
3. The LEDs have been driven by a voltage source of  $12 \text{ V DC}$ .
4. The resistors have been chosen so that for the typical voltage bin of 3B ( $V_f = 2.125 \text{ V @ } 50 \text{ mA}$ ), a current of  $35 \text{ mA}$  flows for every LED. (The resistor values are theoretically calculated.)
5. The simulations have been carried out at an ambient temperature of  $25 \text{ °C}$ .
6. The simulation results were recorded instantaneously, after having had current applied directly from a power supply.

Please note that thermal effects, though not been taken into consideration for the individual simulations, are discussed, generally, at chapter "C. Thermal considerations".

### Circuit topology 1: serial circuit

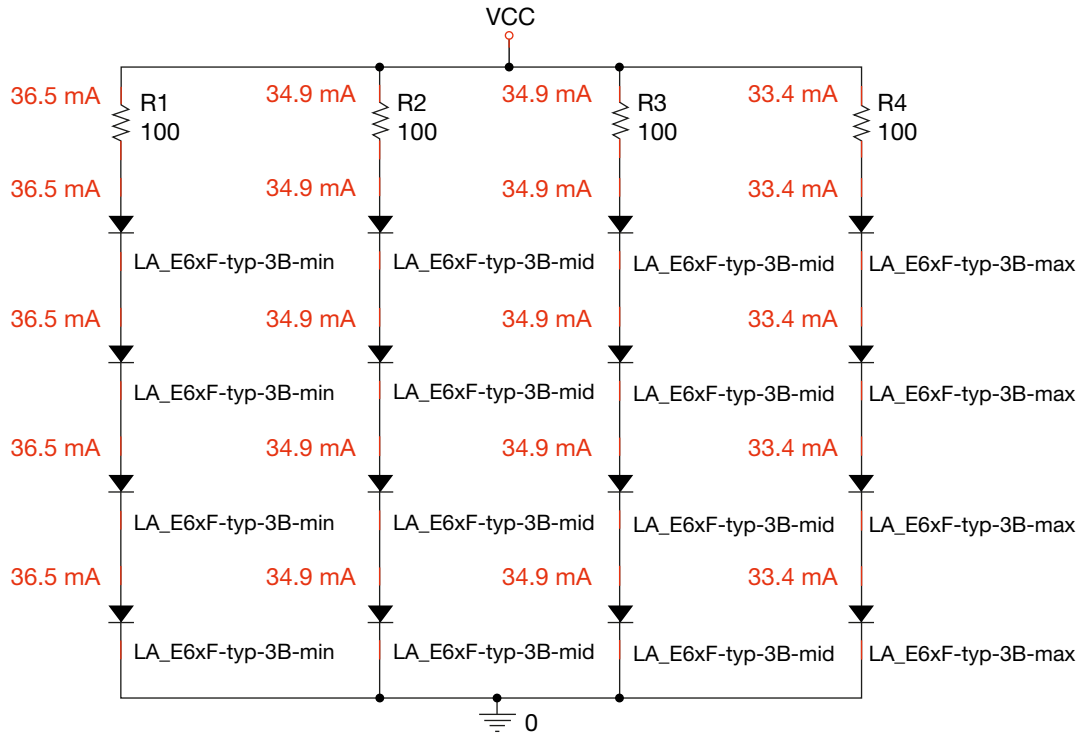
A serial circuit provides a lot of advantages but has also one disadvantage that should be considered when decided for a serial design.

**Serial circuit simulation.** Figure 5 shows the simulation of a serial circuit. The forward current of the simulated LEDs is  $34.9 \text{ mA}$  ( $\sim 35 \text{ mA}$ ) at the middle two

strings. For the LEDs from the lower forward voltage group, the forward current is 36.5 mA. For the LEDs from the upper limit of the forward voltage group, the forward current is 33.4 mA. In the worst case, the overall current variation in this circuit is 35 mA  $\pm$  ~ 5 %.

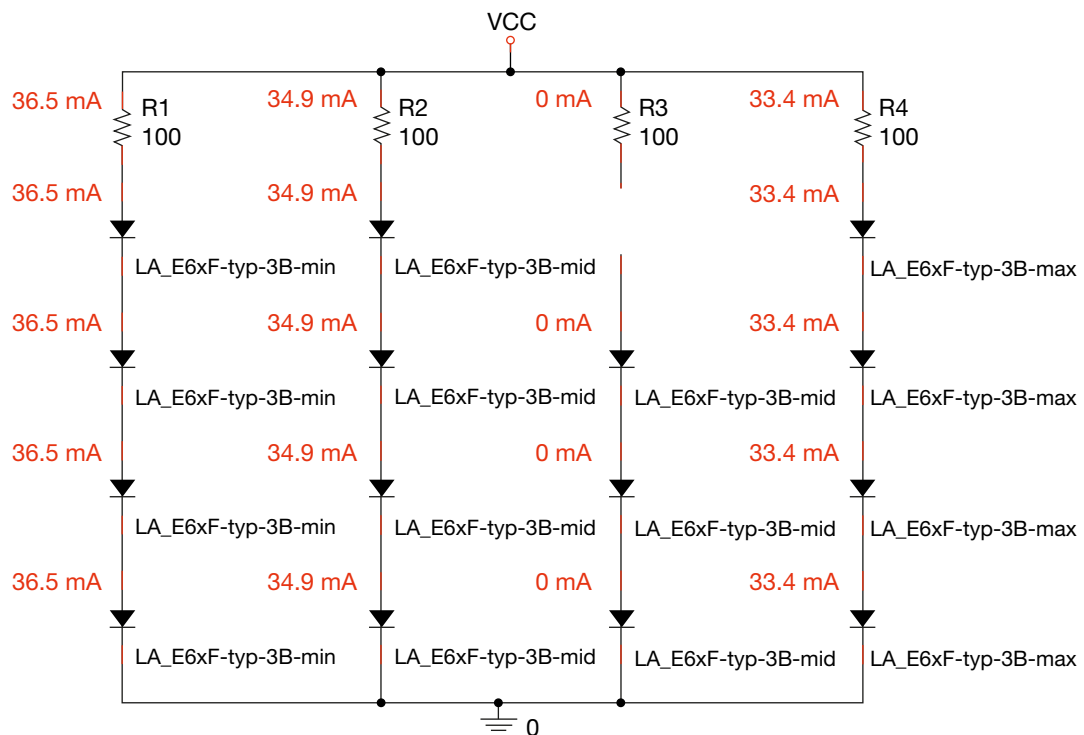
The subsequent effect of temperature on appearance is less profound in this circuit than in circuit topology 2 (matrix circuit) due to less variation in the forward current of the LEDs.

Figure 5: Simulation of a serial circuit



**Serial circuit, one LED failed.** The simulation in Figure 6 shows that the failure of one LED causes the remaining LEDs in that string to fail. As a result, the total current drops from 140 mA to 105 mA, approximately, but the current of the LEDs in the remaining strings is unaffected.

Figure 6: Simulation of a serial circuit, one LED failed



### Circuit topology 2: matrix circuit

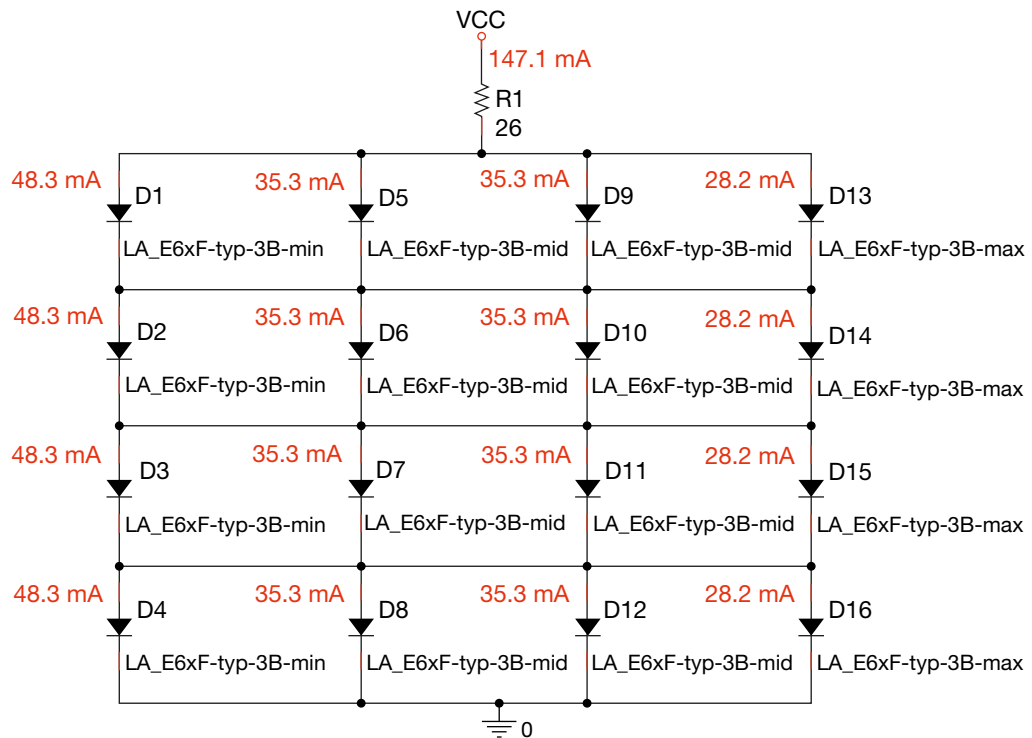
Matrix connections are the easiest way to design redundant and reliable systems. It works quite well for low and mid power LEDs with tight  $V_F$ -Binning e.g. 100 mV or even lower. It is beneficial to design circuits between three and six strings.

Before connecting high power LEDs in a certain matrix combination, a closer look to the I-V characteristics has to be done. Also worst case simulations can help to estimate the circuit behavior in terms of current distribution and resulting module homogeneity.

**Matrix circuit with one resistor for the complete circuit.** As the simulation in Figure 7 shows the forward current for the LEDs with the typical forward voltage is 35.3 mA ( $\sim 35$  mA). For the LEDs from the lower forward voltage group, the forward current is 48.3 mA. For the LEDs from the upper limit of the voltage group, the forward current is 28.2 mA. In the worst case, the overall current variation in this circuit is  $35 \text{ mA} \pm \sim 40 \%$ . This leads to a variation of the brightness which could be seen by the customer.

The forward voltages of the LEDs have a negative temperature coefficient. Accordingly, as the temperature increases, the forward voltage decreases while the forward current increases. In the case of this simulation, the current for the LEDs with 48.3 mA would increase more than for the LEDs with 28.2 mA. The variation of current within the complete circuit would therefore increase.

Figure 7: Simulation of a matrix circuit with one resistor for the complete circuit



### Matrix circuit with one resistor for the complete circuit, one LED failed.

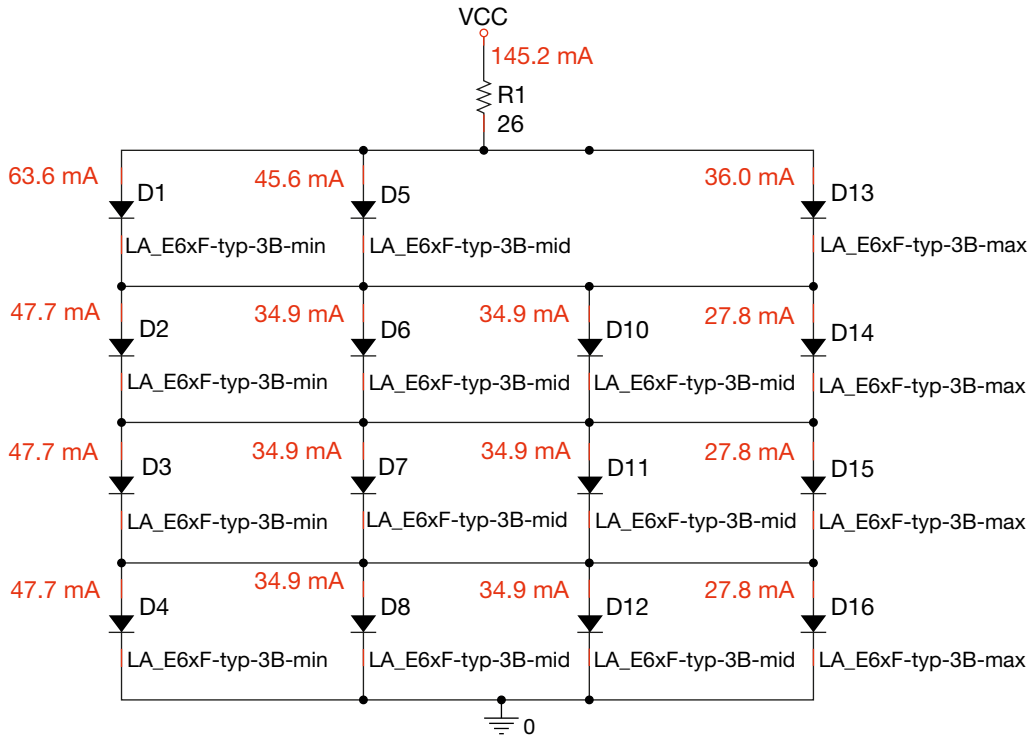
When one LED fails like in simulation in Figure 8, two effects can be observed:

- First, the total current flowing through the complete matrix drops slightly as the equivalent resistance of the circuit increases.
- Second, and more significantly, the three LEDs that are parallel to the failed LED pull more current. In the worst case this means that a LED from the lower limit of the voltage group will pull 63.6 mA.

Due to the small change in current registered by the failure of a single LED, the failure can not be easily or economically detected by current sense; only the failure of the complete circuit can be detected.



Figure 8: Simulation of a matrix circuit with one resistor for the complete circuit, one LED failed



### Advantages and disadvantages of the different circuit topologies

As the two topologies shows, each has its advantages and disadvantage. Accordance with the requirements of the application, the appropriate solution should be selected. Table 1 gives an overview of the advantage and disadvantages of each topology.

Table 1: Advantages and disadvantages of the different circuit topologies

	Serial circuit	Matrix circuit
<b>Advantages</b>	The current for each string can be adjusted very accurately by the resistors	If one LED fails, the remaining LEDs still operate
	Simple circuit design, comparatively low cost for resistors	Simple circuit design, comparatively low cost for the resistors
	The failure of one LED string will not affect the current of the remaining LED strings	
	Due to the significant change in current registered by the failure of a complete string of LEDs, complex failure detection using current sense is made possible	

Table 1: Advantages and disadvantages of the different circuit topologies

	<b>Serial circuit</b>	<b>Matrix circuit</b>
<b>Disadvantages</b>	The failure of a single LED will cause the remaining LEDs in that string to fail	In the worst case the current distribution can be very unsymmetrical. Because of the differences in current, the LEDs do not experience a consistent rise in temperature across the circuit
		The failure of one LED leads to an overdriving of the remaining LEDs to which it was in parallel. This effect is increased when fewer diodes are in parallel, and, when combined with the effects of temperature referenced above, will compromise uniformity to the rest of the circuit and shortened overall life
		Due to the small change in current registered by the failure of a single LED, the failure can not be easily or economically detected by current sense; only the failure of the complete circuit can be detected

### LED circuits recommendation

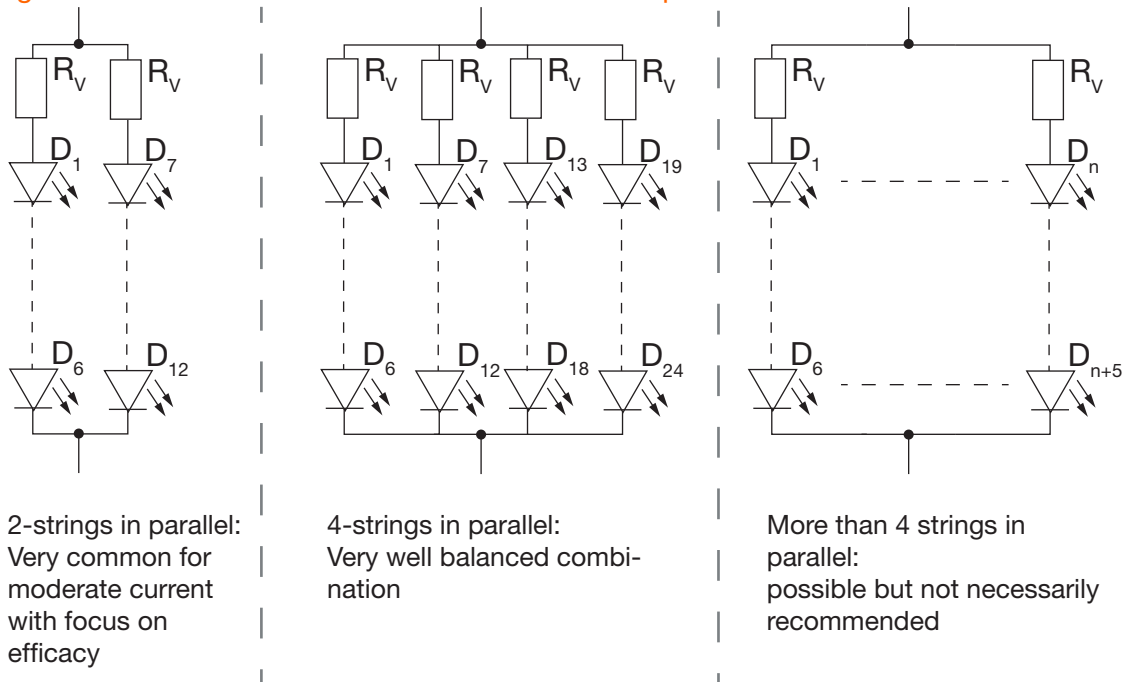
To connect LEDs in parallel, the following design rules should be considered:

1. Use always LEDs of the same type and same manufacturer
2. Use Vf-binned LEDs
  - out of simulation and experience a 100 mV binning per chip is mandatory to ensure parallel operation for low and mid power LEDs.
  - for high power LEDs the same rules have to be followed but it is advisable to double check the design by our Application-Engineering-Team
3. Try to connect several LEDs in series and than the resulting strings in parallel
  - the serial LED connection will improve the statistical string voltage
  - more than 6 LEDs in series will not further improve the string voltage averaging
4. Try to have so many strings parallel to ensure the max. allowed LED current will not be exceed in case you lose one string

5. to minimize the voltage mismatch operate the LEDs around the binning current
6. Do not exceed the operation current per LED to have enough buffer  $I_{OP} < 0.7 I_{max}$
7. To avoid current hogging an appropriate thermal design is needed. Try to get parallel connected LEDs or string close to each other. In case there is an mismatch the one LED or the one string will heat up the other one.

Recommended combinations for this topology (Figure 9) would be a two string solution for a application with focus on efficacy or a 4 strings solution for a well balanced setting. More than 4 strings are possible but not recommended.

Figure 9: Recommended combinations for LEDs in parallel



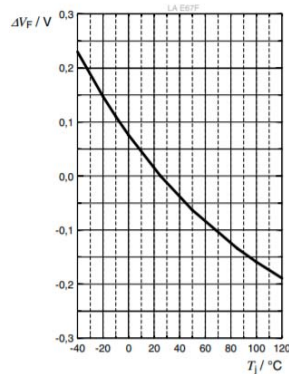
## C. Thermal considerations

The thermal design must be considered for all LED circuits. The higher the junction temperature  $T_j$  rises, the lower the forward voltage  $V_F$  gets, causing the current in the circuit to increase. The change in forward voltage  $V_F$  as a function of the junction temperature  $T_j$  can be seen in the data sheet (Figure 10 shows an example of the data sheet entry of the LA E6xF).

Figure 10: Example of the forward voltage characteristic curve

### Forward Voltage <sup>6)</sup>

$$\Delta V_F = V_F - V_F(25^\circ\text{C}) = f(T_j); I_F = 50\text{ mA}$$



## D. Conclusion

Essentially, there are two ways to design a cluster of LEDs, a serial circuit or a matrix circuit with one resistor for the entire circuit. Each of these possibilities has advantages and disadvantages (see Table 1) that will be dependent upon the end application and the respective requirements therein. For each circuit topology, especially so for the matrix circuit (Figures 7 and 8), the distribution of current within the circuit is critical. The circuit must be designed that the LEDs do not get overdriven and that the LEDs do not overheat: increasing current results in increasing temperature and this again results in increasing current until such an equilibrium is reached. It is exacerbated in matrix circuits by having just the single resistor for the entire circuit.



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