

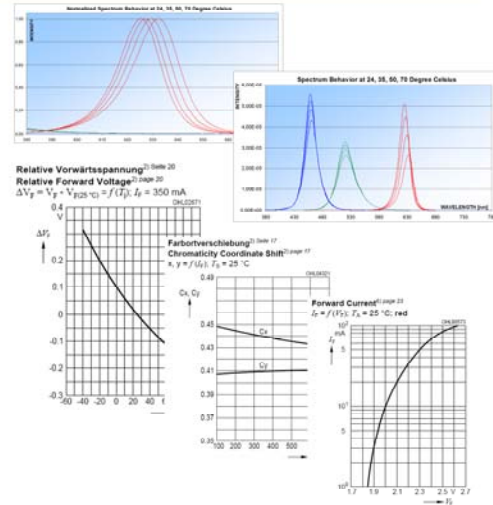
Welcome to this presentation on Driving LEDs – Resistors and Linear Drivers, part of OSRAM Opto Semiconductors' LED Fundamentals series.

In this presentation we will look at:

- Simple resistor based current regulation for LED systems
- Use of linear drivers to regulate current in an LED system

## Introduction

- Proper driving of LEDs is required to address some of the fundamental variations that all LEDs may have due to manufacturing tolerances.
- There are different methods used to drive LEDs. These methods can be very simple or complicated, depending on the application.
- Some of the key parameters needed to choose proper driving method include expected  $T_j$  (Junction Temperature), expected  $V_f$  mismatch between LEDs, color accuracy required at the system level, and if dimming of the LEDs is required for the application.



LED Fundamentals | Driving LEDs - Resistors and Linear Drivers| Page 2

**OSRAM**  
Opto Semiconductors

Just like any other electronic component, LEDs should be driven properly for improved efficacy, better reliability, and longer lifetime. Because of some of the fundamental variations, such as  $V_f$  mismatch between LEDs and color variation within the same bin, even more care needs to be taken when deciding what type of driving method is suitable for LEDs in a particular application.

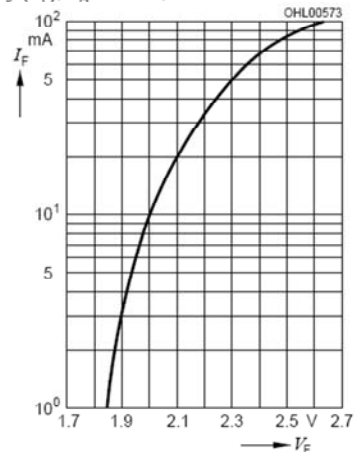
Some of the key parameters that play a major role in selecting the proper driving method are: expected junction temperature of the LED, expected  $V_f$  mismatch between LEDs and/or LED strings, color accuracy required, and whether or not dimming is required.

## Need for Current Regulation in LED Systems

- The I-V characteristics of an LED plays a key role in deciding what type of regulation is best suited for driving LEDs.
- Due to the fact that a small increase in voltage, once the threshold is reached, will significantly increase current through an LED, regulating current is more appropriate for driving LEDs.
- Also, current regulation is required in LED systems to control and maintain:
  - » Color shift vs LED current
  - » Flux or light output vs LED current

Forward Current<sup>6)</sup> page 23

$I_F = f(V_F); T_A = 25\text{ }^\circ\text{C}; \text{red}$

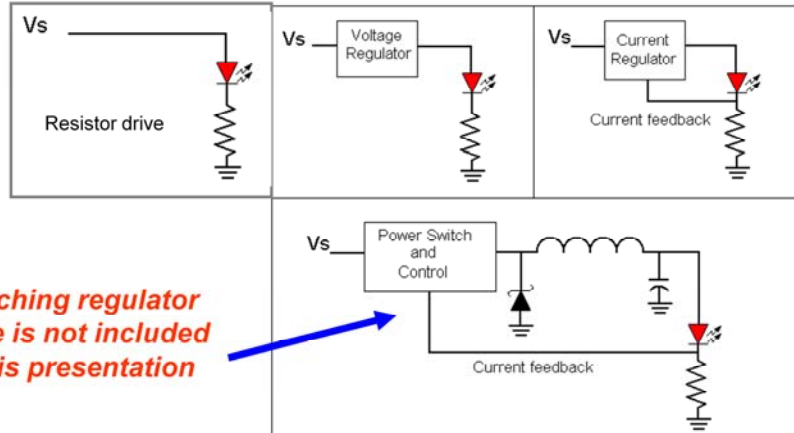


LED Fundamentals | Driving LEDs - Resistors and Linear Drivers| Page 3

**OSRAM**  
Opto Semiconductors

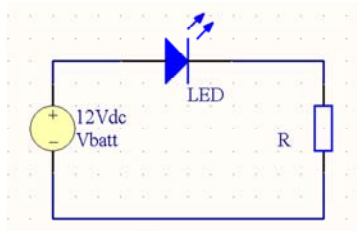
As previously mentioned, an understanding of the electrical, optical, and thermal characteristics of an LED is required to properly select a driving method for an LED circuit or system. Because LEDs have an I-V characteristic that is similar to standard diodes, they are more effectively driven with a constant current source than with a fixed voltage source. Also, optical characteristics such as color shift vs LED current, and thermal characteristics such as  $V_f$  and color shift vs junction temperature of an LED, also play key role in selecting the proper driving method.

## Driving Methods



There are at least three different ways of driving LEDs that can provide constant current to LED circuits and systems. They are resistor or discrete based driving, linear regulator based driving, and switching regulator based driving. In this presentation, discrete based driving and linear regulator based driving are examined.

## Resistor Drive – Very Inefficient



**Very simple** Ohms Law

**solution**

$$I_f = \frac{(V_{batt} - V_f)}{R}$$

Where  $I_f$  is LED current,  
 $V_f$  is LED's forward voltage  
 and  $V_{batt}$  is the supply voltage

If LED current of 350mA is required:

Using the  $V_f$  VS  $I_f$  Graph, the  $V_f$  of the LED at 350mA would be 3.2V

Using Ohms Law we calculate the value of the resistor:

$$(12V - 3.2V) / .350A = 25.1 \text{ Ohms}$$

The power dissipation of the resistor would be

$$(.350A * .350A) * 25.1 \text{ Ohms} = 3.08 \text{ Watts}$$

**Very inefficient**

This is just an example. Power wasted on the resistor is a function of source voltage. The smaller the difference between voltage source and  $V_f$  of the LED, the less power wasted on the resistor.

Discrete based driving can either be a simple resistor to regulate LED current or it can be based on a transistor.

In this example, simply applying ohm's law will give the resistor value for a specific current, which is 350mA in this case. Also, the power dissipated in the resistor can be calculated by using the  $I^2$  equation.

Even though this is the simplest way of driving LEDs, this is also a less efficient way of driving LEDs. As seen in this example, depending on the source voltage, the power wasted on the resistor can be significant.

## Resistor Drive - Change in Vf of LEDs

- Vf difference can come from two sources:
  - » Vf difference comes from process variation during manufacturing.  
(typically in the range of ~250mV)
  - » Change in Vf due to junction temperature (Tj) of the LED.

- Graph on the right shows change in Vf due to Tj.

- For the same circuit on the previous slide, with a supply voltage of 5V, a change in Vf of 250mV will result in the following LED current:

$$\text{Resistor} = (5V - 3.2V) / 350\text{mA} = 5.2 \text{ ohms}$$

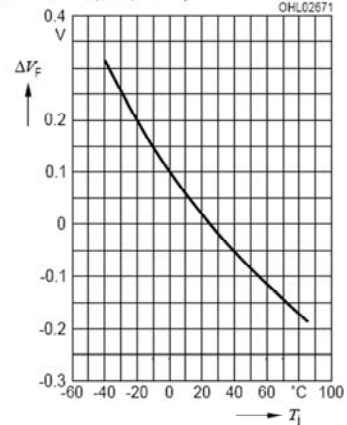
$$(5 - 3.45) / 5.2 = 304\text{mA} \text{ OR}$$

$$(5 - 2.95) / 5.2 = 394.2\text{mA}$$

Relative Vorwärtsspannung<sup>2)</sup> Seite 20

Relative Forward Voltage<sup>2)</sup> page 20

$$\Delta V_F = V_F - V_{F(25^\circ\text{C})} = f(T_j); I_F = 350 \text{ mA}$$

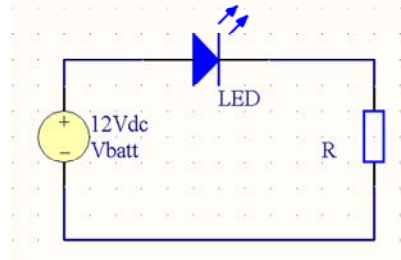


When a resistor is used to regulate LED current, the current can vary depending on the Vf of the LED. The change in current due to Vf variation may or may not be significant and is highly dependant on the application. For instance, this may be significant when multiple color LEDs are mixed to achieve a target color point.

Even with a Vf difference of 250mV, which is typical for LEDs, the LED current can vary between 304mA and 394mA for the same resistor.

## Resistor Drive - Source Voltage Tolerances

- The tolerances on a voltage source will impact LED current in resistor based current regulation.
- Assuming a +/-10% tolerance, which is very reasonable, on the voltage source for the same circuit, the LED current can vary between 302.8mA and 398.4mA.
- The change in LED current will impact the following:
  - » Flux or light output
  - » Color shift due to LED current
  - » Efficacy of the LED/ circuit/ system



If the voltage source had a tolerance of +/- 10%:  
10% of 12V is 1.2V

With tolerance of +10%, LED current would be  
 $(13.2V - 3.2V) / 25.1 \text{ Ohms} = 398.4\text{mA}$

With tolerance of -10%, LED current would be  
 $(10.8V - 3.2V) / 25.1 \text{ Ohms} = 302.8\text{mA}$

LED Fundamentals | Driving LEDs - Resistors and Linear Drivers| Page 7

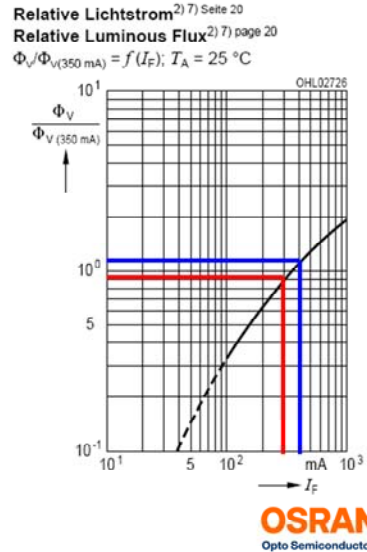
**OSRAM**  
Opto Semiconductors

One of the key issues with resistor based driving is the variation in source voltage. Changes in source voltage will directly impact LED current. Any source voltage will have some tolerances and having a +/-10% tolerance is very common. A 10% tolerance can change the LED current to be between 300mA and 400mA where the actual calculated LED current should be 350mA.

Any change in LED current is not desired. A change in LED current will have an impact on flux output, which may increase or decrease total light output of a system.

## Resistor Drive - Flux Varies with LED Current

- Flux at 302mA is ~90% of flux at 350mA
- Flux at 398mA is ~115% of flux at 350mA
- For calculation purposes, if flux at 350mA is assumed to be 100lm:
  - » Flux at 302mA is ~90lm
  - » Flux at 398mA is ~115lm
- If resistor based regulation is used in a system where the source voltage has a tolerance of +/- 10%, the light output can vary.



LED Fundamentals | Driving LEDs - Resistors and Linear Drivers| Page 8

To explain impact on flux at different LED currents, an example is shown in this slide. Flux output at 300mA is only 90% of that at 350mA and at 400mA, it is 115% of that of 350mA.

The calculation of flux variation reveals that with just one LED, the flux can vary up to 25lm. In a system with multiple LEDs, the change in flux can be significant.

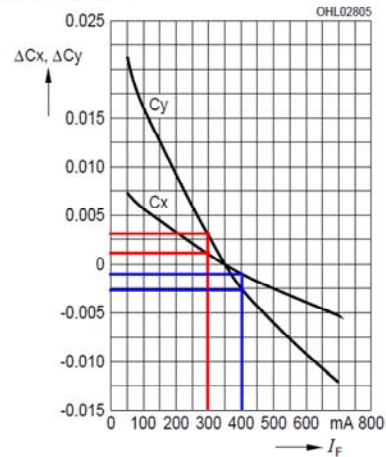


## Resistor Drive- Color Point Can Vary with LED Current

- Consider the same circuit analysis on the previous slide, in which the LED current can be either 302mA or 398mA.
- Based on the graph on the right, the Cx, Cy shift at an LED current of 302mA can be ~-0.00125 and ~-0.00250, respectively.
- At an LED current of 398mA, the Cx, Cy shift can be -0.00125 and -0.00250, respectively.
- The color shift due to varying LED current cannot be addressed in a resistor drive.

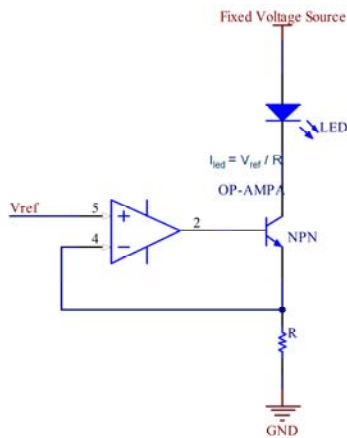
### Chromaticity Coordinate Shift<sup>2)</sup> page 20

$$x, y = f(I_F), T_A = 25^\circ\text{C}$$



Also, there will be a slight color shift when LED current is changed. Depending on the application, this should be taken into account when selecting the correct driving method for an LED application. The color shift for two different currents is shown on this slide.

## A Slightly Different Approach to Resistor Drive



How does the circuit work?

1. The op-amp automatically adjusts its output (NPN's base drive) to bring its negative input equal to the positive input. This means that  $V_{ref} = V_R$  (voltage across resistor "R").
2. A simple application of Ohms law would make current through R and the LED  $= V_{ref} / R$ .
3. NPN delivers the current, and because the NPN's currents are related by  $I_c \approx I_e$ , the same current that is developed through R must also flow through the LED.

This slide shows a different approach to resistor based driving using a transistor and an OP-AMP. In this way of driving, the  $V_f$  mismatch and source variations will not change the LED current.

The LED current in this circuit will be  $V_{ref}$  divided by Resistor R.

The addition of a transistor and an op-amp can be justified in an application where impacts of  $V_f$  mismatch and source variation cannot be tolerated.

## Advantage and Disadvantages of Resistor Drive

### The advantages of resistor based regulation includes:

- Cost effective solution
- Very simple and ideal for space constrained applications
- Possible solution for applications that have a lot of variables and issues such as flux and Vf variations that don't need to be addressed, eg. flashlights/ torch lights

### However, there may be issues with this type of driving method:

- Very inefficient
- Vf mismatch or variation due to Tj cannot be addressed with this method
- Supply voltage variation is not addressed
- Flux variation cannot be addressed

### The OP-AMP + Transistor method:

- Source/ supply voltage variation issue addressed
- Vf mismatch or variation due to Tj will be addressed
- More stable LED current due to corrections related to the previous two issues

LED Fundamentals | Driving LEDs - Resistors and Linear Drivers| Page 11

**OSRAM**  
Opto Semiconductors

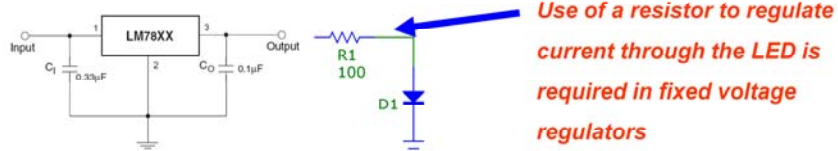
In this slide the advantages and disadvantages of methods discussed so far are analyzed.

A resistor based current regulation is very cost effective and very simple for space constrained application, and ideal for applications where color, flux, and Vf mismatch are not a significant concern, such as flashlights or torch lights. However, with a resistor based solution, Vf mismatch, variation in supply voltage and flux, and color shift cannot be addressed. It is also very inefficient.

With the OP-AMP + transistor method, source variation and Vf mismatch are addressed.

## Linear Regulators

Linear regulators can either be *fixed voltage* or *constant current*



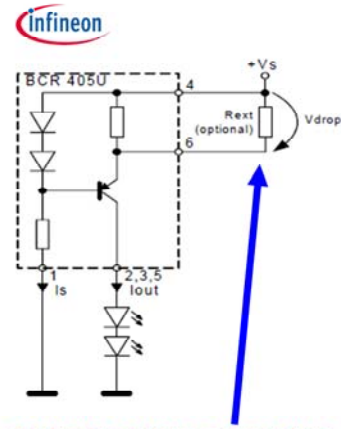
$I_f$  is LED current ← 
$$I_f = \frac{(V_{out} - V_f)}{R}$$

- Fixed voltage regulator compensates for source voltage variations, but does not compensate for variations in the LED forward voltage.
- If being used by other circuits in an LED system, can also be used for LED drive.

Aside from resistor based regulation, LEDs can also be driven using linear regulators. Linear regulators can either be fixed voltage or constant current. In fixed voltage linear regulators, a resistor is also required to set proper LED current.

## Linear Regulator Based Driving

- **Constant current linear regulators** are very simple to design and are widely used in LED systems.
  - National Semi, Infineon Technologies, Zetex, and TI are some of the suppliers to name a few.
- 
  
 LED Light for you  
 powered by OSRAM
- Linear regulators:
    - Eliminates changes in source voltages issue.
    - Maintains constant current and brightness in LEDs.
    - Compensates for changes in LED forward voltage.



*minimal passives, a capacitor  
and a resistor in most cases*

LED Fundamentals | Driving LEDs - Resistors and Linear Drivers| Page 13

**OSRAM**  
Opto Semiconductors

A constant current linear regulator is preferred over fixed voltage linear regulator because it can take a wide range of voltage and output with a set constant current, ideal for driving LEDs. Because the output is constant current, Vf mismatch between LEDs is not a concern with constant current linear regulators. Also, a linear driver requires very few passive components, in many cases only a resistor and/or a capacitor.

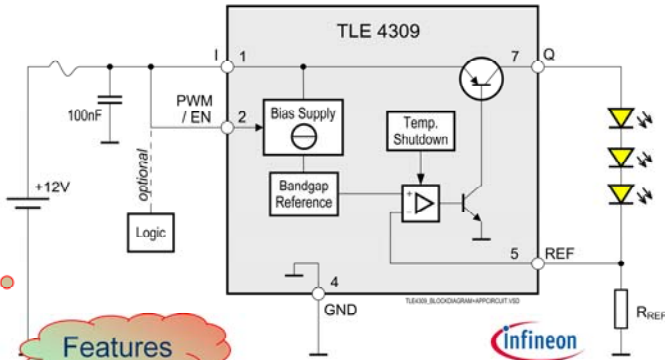
## Linear Regulator Based Driving

infineon



**TLE 4309G**

- Adjustable Output Current up to 500 mA
- Low dropout voltage
- PWM Input (dimming)
- Over-Temperature Protection
- Short Circuit Protection to GND and  $V_{supply}$



Features

- Reverse Polarity Protected
- Max. Operating Voltage: 24 V
- Max. Input Voltage: 45 V
- Package PG-TO-263-7

LED Fundamentals | Driving LEDs - Resistors and Linear Drivers| Page 14

**OSRAM**  
Opto Semiconductors

There are many different constant current linear regulators on the market. In many cases, the passive components that are required to complete the linear driver circuit are very minimal. A picture of Infineon's TLE4309 and its features are shown here for reference.

## Linear Regulator Based Driving

BCR40X



- Total forward voltage must be lower than the supply voltage (more like a buck type)
- Efficiency is not as good as a switching regulator.
- Some of the features of BCR40X are listed on the right
- Linear regulators are ideal for low current LED applications
- If higher current is needed, then **external circuitry** is required

- One of the lowest cost LED drivers in the industry
- Output current adjustable by external resistor from 10mA to 65mA
- Suitable for PWM for dimming
- Negative temperature coefficient serves as protection for LED's
- Pretested output current
- Low voltage drop

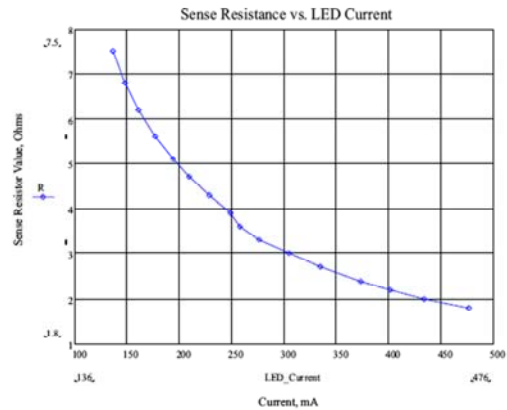
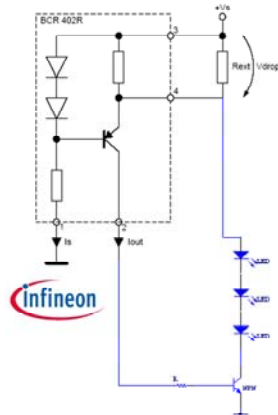
LED Fundamentals | Driving LEDs - Resistors and Linear Drivers| Page 15

**OSRAM**  
Opto Semiconductors

One of the issues with linear regulators is that the LED current is limited to tens of mA due to the maximum power rating on the regulator itself. If higher current LEDs are required, external circuitry should be in place.

## Linear Regulator Based Driving

With an external circuit, the LED current can be made as high as 500mA.



LED Fundamentals | Driving LEDs - Resistors and Linear Drivers| Page 16

**OSRAM**  
Opto Semiconductors

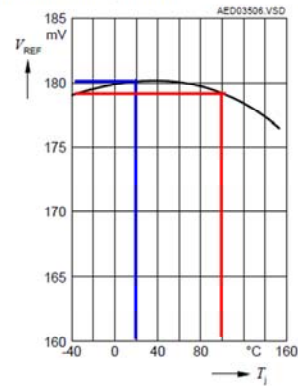
Pictured in this slide is the external circuitry required to boost LED current using Infineon's BCR402R. If more than 65mA is required, the LED current can be taken up to 500mA by adding a transistor.



## How Stable is Linear Regulator Based Driving?

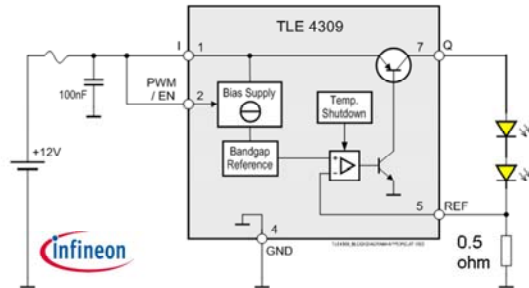
- Linear regulators are **very stable** over a wide range of temperatures.
- The temperature characteristics of the BCR4X family from Infineon Technologies is shown on the right.
- The reference voltage, which is directly proportional to LED current at two different temperatures (20°C and 100°C), was examined.
- The delta between 20°C and 100°C is only about 1mV, which means that the LED current will be very stable over a wide range of temperature.

Reference Voltage versus Junction Temperature



One of the key advantages of linear regulators is the stability of linear drivers over temperature. The stability of the BCR400 series over a wide range of operating temperature is illustrated here. As seen from the graph, the change in reference voltage between 20°C and 100°C is only one milli volt.

## How Much Power Wasted in Linear Regulators?



Power on TLE4309 ~  $(V_{in} - V_{out}) * \text{Current}$  (LED current = 350mA)  
 ~  $(12 - 6.4) * 0.35$  ( $V_f$  of two LEDs = 6.4V)  
 ~ 2W

As with resistor based driving, linear regulators are also very inefficient. The difference in input and output voltages are simply wasted as heat within the regulator itself. Therefore, wasted power is directly proportional to how wide the difference is. The difference between input and output voltages should be taken into consideration when designing with linear drivers, to ensure the power rating on the driver is not exceeded.

## Advantages and Disadvantages of Linear Drive

### Advantages of linear current regulators:

- Better/more stable regulation compared to resistor regulation
- Vf mismatch between LEDs addressed
- Vf change due to temperature is addressed
- Stable current regulation over a wide temperature range

### Disadvantages of linear current regulators:

- Not very efficient
- Costly compared to resistor drive
- Can only be used when total Vf of LEDs less than the supply voltage
- If it is a fixed voltage type linear regulator, use of a resistor is still required

Linear regulators are very simple to design and a cost effective solution for driving LEDs. Also, with linear drivers, the fundamental variations such as Vf mismatch, are addressed. As with any driving method, there are also disadvantages, which are listed here.

## Summary

In summary, the table below compares resistor drive and linear drive in LED systems/ circuits.

	Resistor Drive	Linear Regulator
Vf mismatch between LEDs addressed	NO	YES
Vf change due to temperature addressed	NO	YES
Source voltage variation addressed	NO	YES
Tight current regulation	NO	YES
Simple solution	YES	YES
Costly solution	NO	YES (compared to resistor driver)
Efficient solution	NO	NO
Stable over wide-range of temperature	NO	YES

In conclusion, resistor based and linear regulator based driving are the simplest and most cost efficient ways of driving LEDs, even though they come with some disadvantages. Linear drivers address some of the fundamental variations that LEDs have, but still isn't a very efficient way of driving LEDs. There are other available options when it comes to driving LEDs.

## Disclaimer

All information contained in this document has been checked with the greatest care. OSRAM Opto Semiconductors GmbH can however, not be made liable for any damage that occurs in connection with the use of these contents.

OSRAM Opto Semiconductor GmbH makes no representations and warranties as to a possible interference with third parties' intellectual property rights in view of products originating from one of OSRAM Opto Semiconductor GmbH's partners, or in view of products being a combination of an OSRAM Opto Semiconductor GmbH's product and a product of one of OSRAM Opto Semiconductor GmbH's partners. Furthermore, OSRAM Opto Semiconductors GmbH cannot be made liable for any damage that occurs in connection with the use of a product of one of OSRAM Opto Semiconductor GmbH's partners, or with the use of a combination of an OSRAM Opto Semiconductor GmbH's product and a product of one of OSRAM Opto Semiconductor GmbH's partners.

## Disclaimer

This document constitutes neither an offer to sell nor a solicitation to buy or subscribe for securities. Any such offer will be made solely on the basis of the Securities Prospectus yet to be approved by the German Financial Supervisory Authority (BaFin) and published thereafter. The information legally required to be provided to investors will be contained only in the Securities Prospectus.

The information contained herein is not for distribution, directly or indirectly, in or into the United States of America (including its territories and possessions of any State of the United States of America or the District of Columbia) and must not be distributed to U.S. persons (as defined in Regulation S under the U.S. Securities Act of 1933, as amended ("Securities Act")) or publications with a general circulation in the United States of America. This document is not an offer of securities for sale in the United States of America. The securities have not been and will not be registered under the Securities Act and may not be offered or sold in the United States of America absent registration or an exemption from registration under the Securities Act. The Issuer does not intend to register any portion of the offering in the United States of America or to conduct a public offering of the securities in the United States of America. This document is not an offer of securities for sale in the United Kingdom, Canada, Japan or Australia.

LED Fundamentals | Driving LEDs - Resistors and Linear Drivers| Page 22

**OSRAM**  
Opto Semiconductors



**Thank you for your attention.**

LED Fundamentals | Driving LEDs - Resistors and Linear Drivers| Page 23

**OSRAM**  
Opto Semiconductors

Please refer to the LED Fundamental “**Driving LEDs - Switching Drivers**” on this website for additional information.

Thank you for viewing this presentation by OSRAM Opto Semiconductors.