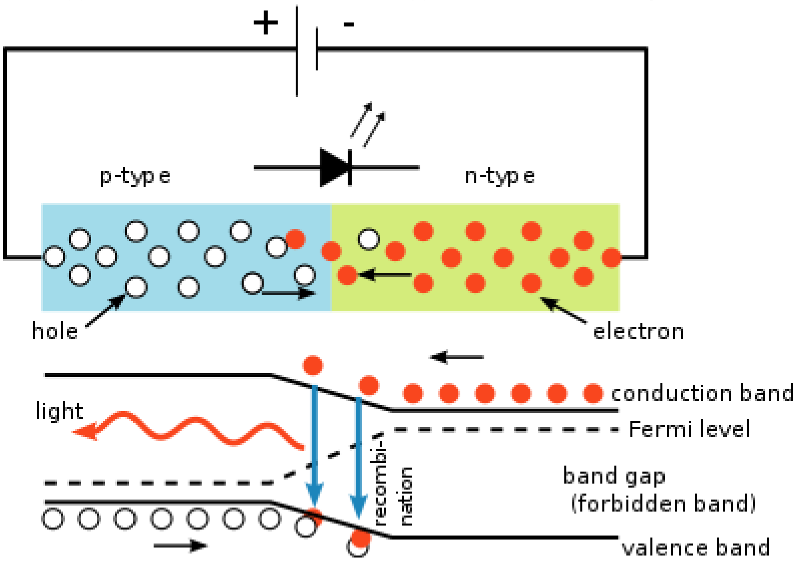
Epigap FAQs

Part 1

1. Optical parameters

1.1. What is a LED?

A LED consists of a chip of semiconducting material doped with impurities to create a p-n junction. Current flows easily from the p-side, or anode, to the n-side, or cathode, but not in the reverse direction. Charge carriers - electrons and holes - flow into the junction from electrodes with different voltages. When an electron meets a hole, it falls into a lower energy level and releases energy in the form of a photon (radiative recombination).



drawing from wikipedia

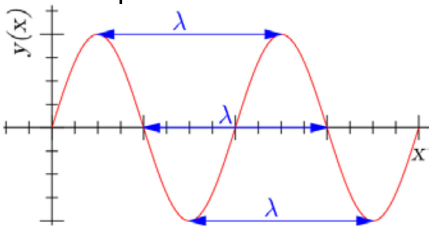
The inner workings of an LED, showing circuit (top) and band diagram (bottom).
The wavelength of the light emitted, and thus its color, depends on the band gap energy of the materials forming the p-n junction. The materials used for the LED have a direct band gap with energies corresponding to near-infrared, visible, or near-ultraviolet light. LED development began with infrared and red devices made with gallium arsenide. Advances in materials science have enabled making devices with ever-shorter wavelengths, emitting light in a variety of colors.

LEDs are usually built on an n-type substrate, with an electrode attached to the p-type layer deposited on its surface. P-type substrates, while less common, occur as well. Many commercial LEDs, especially GaN/InGaN, also use sapphire substrate.
Most materials used for LED production have very high refractive indices. This means that much light will be reflected back into the material at the material/air surface interface. Thus, light extraction in LEDs is an important aspect of LED production, subject to much research and development.

1.2. main optical parameters

1.2.1. wavelength

In physics, the wavelength of a sinusoidal wave is the spatial period of the wave - the distance over which the wave's shape repeats. For the optical spectrum it is often given in nm or µm.



1.2.2. peak wavelength, λ_p

Wavelength with the maximum intensity within the spectrum.

1.2.3. centroid wavelength λ_c

The centroid wavelength λ_c is the wavelength that divides the integral of a spectrum into two equal parts. For symmetrical spectrum, $\lambda_c = \lambda_p$. The centroid wavelength is ideal for characterizing the radiometric properties of LEDs.

1.2.4. dominant wavelength λ_d

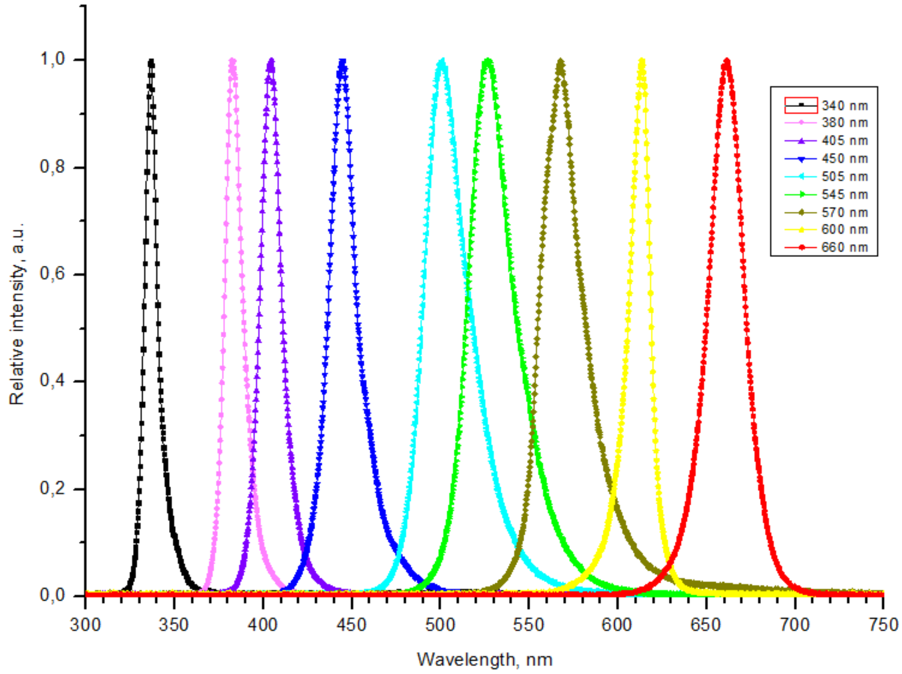
The dominant wavelength describes a (polychromatic) light mixture in terms of a spectral (monochromatic) light that evokes an identical perception in the human eye. That's why dominant wavelength is suitable for color binning of LEDs.

1.3. What wavelength corresponds to what LED color / to what semiconductor material?

Conventional LEDs are made from a variety of inorganic semiconductor materials. The following table shows the available colours with wavelength range, forward voltage (voltage drop) and material:

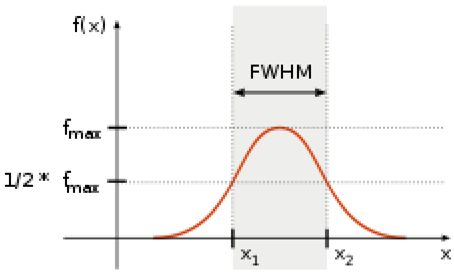
Color	**Wavelength, nm**	**Voltage drop, V_F**	**Semiconductor material**
Infrared	$900 < \lambda <$ 1650 (2700)	$V_F < 1.3$ V	indium gallium arsenide (InGaAs) indium gallium arsenide phosphide (InGaAsP)
Infrared	$\lambda > 760$	$V_F < 1.63$ V	gallium arsenide (GaAs) aluminium gallium arsenide (AlGaAs) indium aluminium gallium arsenide (InAlGaAs), silicon (Si) as substrate - under development
Red	$610 < \lambda < 760$	$1.63 < V_F <$	aluminium gallium arsenide (AlGaAs)

		2.03 V	gallium arsenide phosphide (GaAsP) aluminium indium gallium phosphide (AlInGaP) gallium phosphide (GaP:ZnO)
Orange	590 < λ < 610	2.03 < V_F < 2.10 V	gallium arsenide phosphide (GaAsP) aluminium gallium indium phosphide (AlInGaP) gallium phosphide (GaP)
Yellow	570 < λ < 590	2.10 < V_F < 2.18 V	gallium arsenide phosphide (GaAsP) aluminium indium gallium phosphide (AlInGaP) gallium phosphide (GaP)
Green	500 < λ < 570	1.9 < V_F < 4.0 V	**Traditional Green:** gallium phosphide (GaP) aluminium indium gallium phosphide (AlInGaP) aluminium gallium phosphide (AlGaP) indium gallium nitride (InGaN) / gallium nitride (GaN) **Pure Green:** gallium phosphide (GaP:N)
Blue	450 < λ < 500	2.48 < V_F < 3.7 V	zinc selenide (ZnSe) indium gallium nitride (InGaN) silicon carbide (SiC) as substrate silicon (Si) as substrate - under development
Violet	400 < λ < 450	2.76 < V_F < 4.0 V	indium gallium nitride (InGaN)
Purple	multiple types	2.48 < V_F < 3.7 V	Dual blue/red LEDs, blue with red phosphor, or white with purple plastic
Ultraviolet	λ < 400	3.1 < V_F < 4.4 V and more	gallium nitride (GaN) (365 nm) diamond (235 nm) boron nitride (215 nm) aluminium nitride (AlN) (210 nm) aluminium gallium nitride (AlGaN) alminium gallium indium nitride (AlGaInN) - down to 210 nm
Pink	multiple types	V_F ~ 3.3 V	Blue with one or two phosphor layers: yellow with red, orange or pink phosphor added afterwards, or white phosphors with pink pigment or dye over top. Sometimes two different LED chips in one package.
White	Broad spectrum	V_F = 3.5 V	Blue / violet / UV LED with yellow phosphor



1.4. spectral bandwidth (FWHM), $\Delta\lambda_{0.5}$

FWHM meaning full width at half maximum



typical spectral widths (FWHM) of LEDs, usually increasing with increasing peak wavelength ($\Delta\lambda_{0.5}$ is about 5% of λ_P)

Table. Typical measured values of spectral widths for LEDs with different wavelengths.

wavelength, nm	spectral width, nm
340	9
365	9…10
400	18
430	14
450	17
505	29
525	27
574	13…27
590…595	14
615	14
660	22
740	27
810	28
830	27…40
850	29
870…880	42
1000	55
1200	65
1322	78
1400	80
1458	81
1548	97
1600	100

1.5. other spectral properties

1.5.1. What are the differences between LEDs fabricated on different substrates?

The substrate is responsible for crystal lattice match or mismatch, thermal properties (thermal conductivity) and mechanical stability.

Blue emitting LEDs are typically manufactured on sapphire (Al_2O_3) substrates, sometimes on silicon carbide (SiC). Other substrates are GaN, AlN, ZnO and Si. For most IR-LEDs GaAs and InP are the substrate materials of choice.

1.5.2. “Green gap”

In the wavelength range 535 … 570 nm LEDs with high power are hardly available. New generation green LEDs manufactured from InGaN/GaN are far more efficient and brighter than conventional green LEDs produced with non-nitride material systems like GaP or AlInGaP.

1.5.3. spectral purity of radiation

LEDs based on AlInGaP/GaAs, AlGaAs/GaAs sometimes have an unwanted second spectral peak coming out of the GaAs substrate. If high spectral purity is needed another substrate has to be used.

1.6. energetic parameters

1.6.1. radiant power (Φ_e in mW)

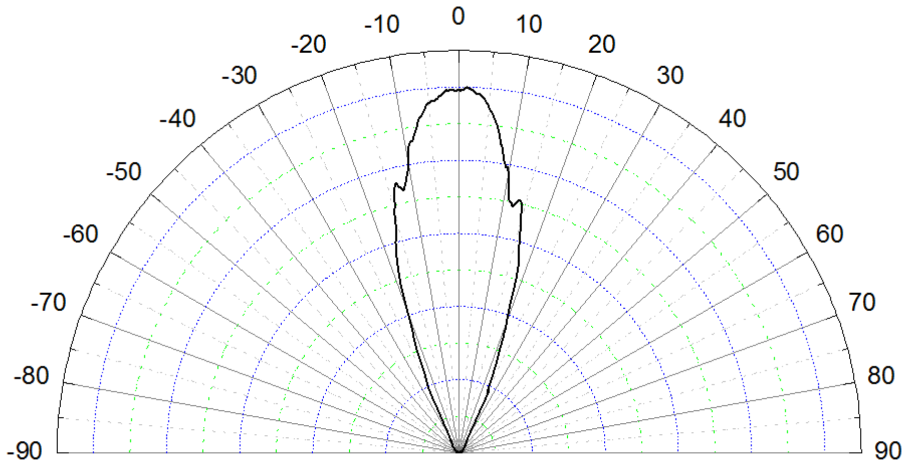
or radiant flux is the power emitted by the LED in the optical spectrum (both visible and invisible). It is usually given in mW.

1.6.2. radiant intensity (I_e in mW/sr)

is the optical power emitted by a LED within a certain special angle . It is usually given in mW/sr (Steradian: Please see 1.10.1.)

1.6.3. angle of half intensity ($\phi_{0.5}$ in degrees)

In a radiation diagram, the angle within which the radiant intensity is greater than or equal to half of the maximum intensity. In the following example this angle is about 35°.



1.6.4. measurement of power output

It is standard practice to characterize the output of LEDs in terms of optical power output. This is the quantity which is easiest to measure with a high degree of reproducibility. Since the amount of light (or radiation) a LED generates depends on the value of the forward drive current (I_F), the power output is always stated for a given value of current. Also, the ambient temperature must be specified because the radiant power decreases with increasing temperature, the temperature coefficient is typically -0.9%/K.

The following two methods are used to measure light power output:

1.6.4.1. total power (PO)

This method involves collecting and measuring the total amount of light emitted from the LED regardless of the direction. This measurement is usually done by using an integrating sphere or by placing a very large area detector directly in front of the LED so that all light emitted in the forward direction is collected. The total output power is measured in units of (milli) watts.

The total power method ignores the effect of the beam pattern produced by the LED package. It cannot predict how much light will strike an object positioned some distance in front of the LED. However, total output power measurement is repeatable and quite useful for comparison of LEDs.

1.6.4.2. On axis power (PA)

This method characterizes the LED in terms of axial intensity. Many practical applications require knowledge of optical power directed to a detector at a certain distance from the LED. For exact measurement of this parameter it is necessary that the distance from the LED to the detector and the active area of the detector is specified. This is because the radiation pattern observed for many LEDs is dependent on the distance from the LED (near-field and far-field radiation patterns).

Irradiance (E_e) is the average power density in milliwatts per square centimeter (mW/cm^2) incident onto a surface of diameter (D). Irradiance is a useful measurement technique in the near field of the LED's beam pattern. Measuring the power through an aperture of diameter "D" spaced distance "d" from the LED approximates many real-life applications.

The on-axis power can also be stated as a radiant intensity (Ie) which is the average power per unit of solid angle expressed in units of milliwatts per steradian (mW/sr). To calculate the irradiance at any distance the following formula is applicable.

$Ee = Ie/d^2$ (mW/cm^2),

where:

Ie = radiant intensity (mW/sr)
d = distance (cm)

Ee = irradiance (mW/cm^2)

For example, an LED with a radiant intensity of 150 mW/sr would produce an irradiance of 0.6 $\mu W/cm^2$ at a 5 meter distance.

A LED can be treated as a point source according to the above equation when the spacing between the LED and receiver is at least ten times the LED package diameter. For shorter distances actual measurements of E_e should be performed.

1.6.5. light modulation properties

1.6.5.1. switching times (rise and fall times) of the LEDs

LEDs are rather fast light sources. Rise and fall times vary from nanoseconds to microseconds for different semiconductor materials, structures, sizes and electrical capacity.

Switching times are defined as changing in I_e from 10% to 90% (rise time) and from 90% to 10% (fall time).

1.6.5.1. Cut-off frequency

is the frequency above which the power output of a LED has fallen to a given proportion (mostly half or 3 dB) of the power in the passband, for LEDs cut-off frequency is usually a few 10 MHz.

The LED speed can be increased by using small forward pre-biasing. There are special driver circuits.

1.7. Photometric units (vis spectrum)

1.7.1. luminous flux (Φ_v) in lumen (symbol lm)

is a measure of the total "amount" of visible light emitted by a source and is measured in lumen, symbol: lm. Luminous flux "take into account" the spectral sensitivity of the human eye to different wavelengths.

1.7.2. illuminance (E) in lm/m² or lux

illuminance is measured in lux. One lux is one lumen per square meter.

1.7.3. luminous intensity (I_v) in candela (symbol: cd)

is a measure of visible light (Φ_v in lm) emitted by a light source in a particular direction within a solid angle Ω (in steradian)

$Iv = \Phi v / \Omega$ (1cd = 1 lm/sr)

1.7.4. colour, colour coordinates

All colors can be described in a two-dimensional space, the CIE x,y color coordinates (drawing from Wikipedia)

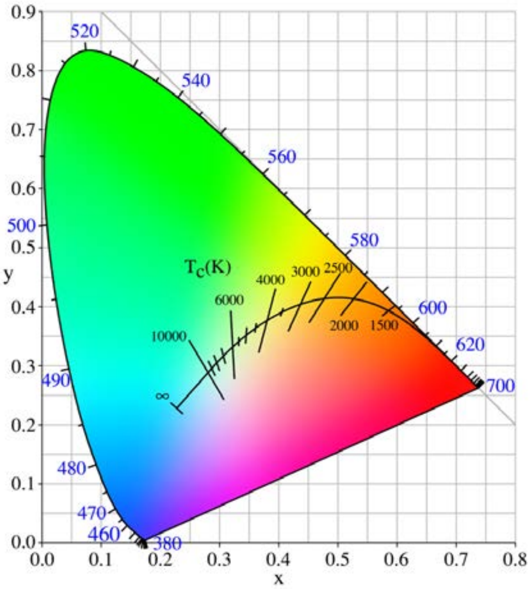


figure: CIE 1931 x y chromaticity space, also showing the chromaticities of black-body light sources of various temperatures, and lines of constant correlated color temperature

1.7.5. Color purity

is a measure of saturation of color (white to fully saturated color). Monochromatic light has the color purity of 1.

1.7.6. Why color coordinates are used to describe the characteristics of white LEDs and not dominant wavelength?

To obtain white light in LED technology, a blue light-emitting die (wavelength 450 nm to 470 nm) is covered with a converter material that is stimulated by blue light and emits a yellow light. The human eye detects the mixture of blue and yellow light as white. Because this mixture cannot be described by a simple dominant wavelength (there are two peaks in the spectrum, as shown in figure below), colour coordinates must be used. The values of these x- and y-coordinates are calculated using the calculation of chromaticity coordinates (CIE).

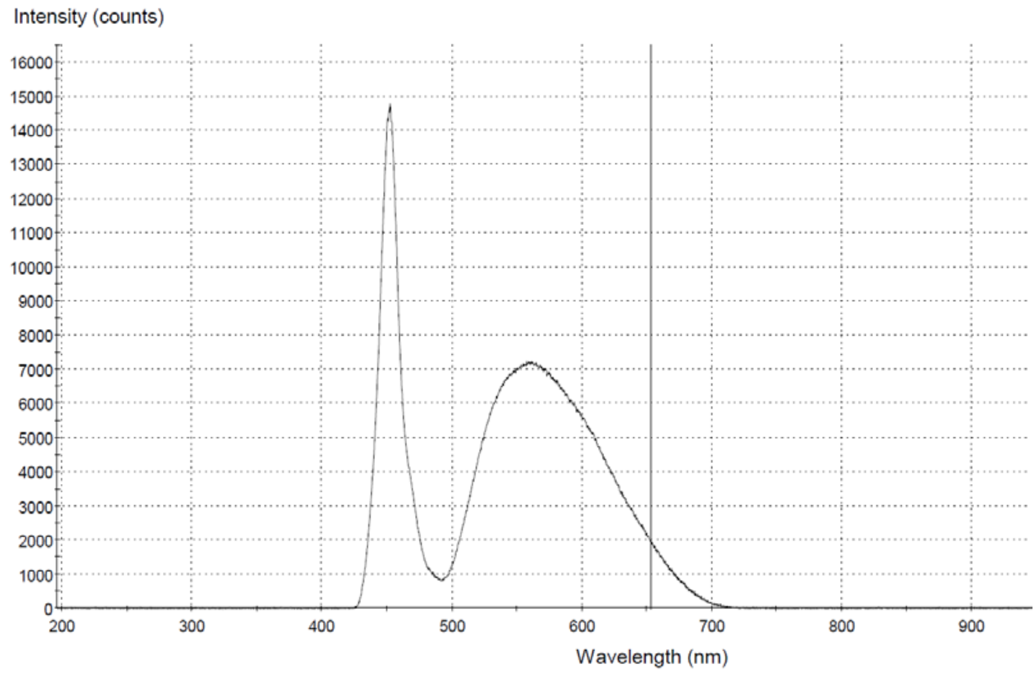


Figure: spectrum of a single-chip white LED.

1.7.7. Correlated color temperature (CCT)

is the absolute temperature (in Kelvin, K) of a blackbody whose chromaticity most nearly resembles that of the light source.

The correlated color temperature (CCT) of a light source gives a good indication of the LEDs general appearance, but does not give information on its specific spectral power distribution. Therefore, two various types of LEDs may appear to be the same color, but their effects on object colors can be quite different.

1.7.8. Color Rendering Index (CRI)

is a quantitative measure of the ability of a light source to reveal the colors of various objects faithfully in comparison with an ideal light source (black body). Light sources with a high CRI are desirable in color-critical applications such as photography and illumination for medical applications (source: Wikipedia)

Best phosphor-based high CRI LEDs have a CRI above 92 with color temperature 2700-4000 K. For general illumination a CRI of 85 is often acceptable.

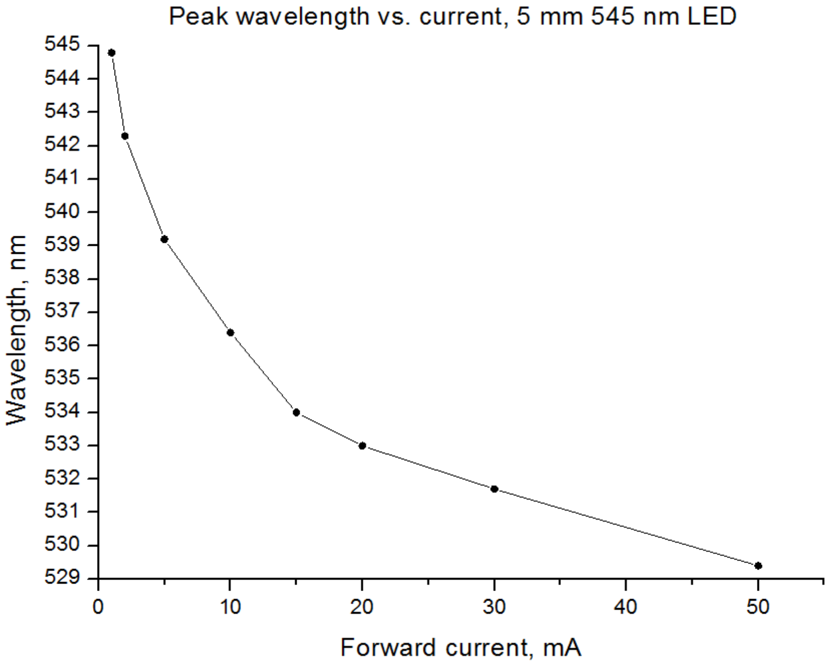
1.8. dependencies of optical parameters of LEDs

1.8.1. dependence of peak wavelength on temperature

Peak wavelength is temperature-dependent and (usually) increases with increasing temperature. This dependence is almost linear.

1.8.3. dependence of peak wavelength on forward current

There is only a weak dependence of λ_p on current; temperature dependence is decisive.



1.8.3. dependence of colour coordinates on temperature

This dependence is generally rather weak, but for green LEDs can be profound. So the spectrum can be efficiently controlled by stabilizing the forward current (and temperature).

1.8.3. Temperature coefficient of output power, luminous flux, luminous intensity

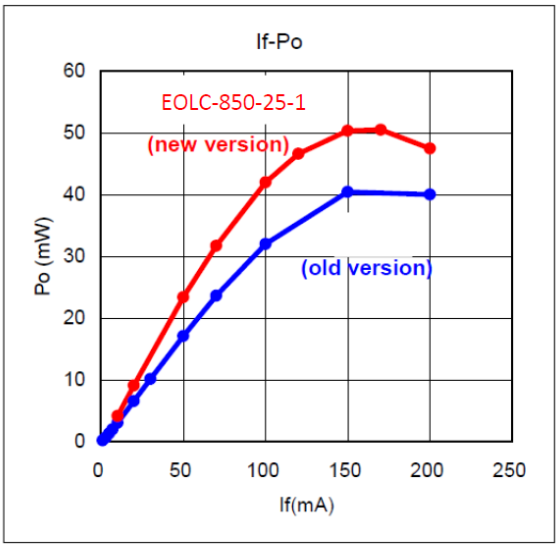
Output power of a LED decreases with increasing temperature. It depends on material used and can be (linear) approximated.

examples:

1.8.4. efficiency vs. drive current

Efficiency usually drops with increasing current.

The output power of a LED rises with increasing forward current. The forward current generates heat inside the LED that causes an increase of junction temperature. As the junction temperature increases efficiency drops (rise in temperature results in a decrease of radiative recombination efficiency). Thus dependence of output power from forward current tends to saturation. The degree and range of linearity differs for different LED types.



*LED die was mounted on TO-18 header without resin coat.

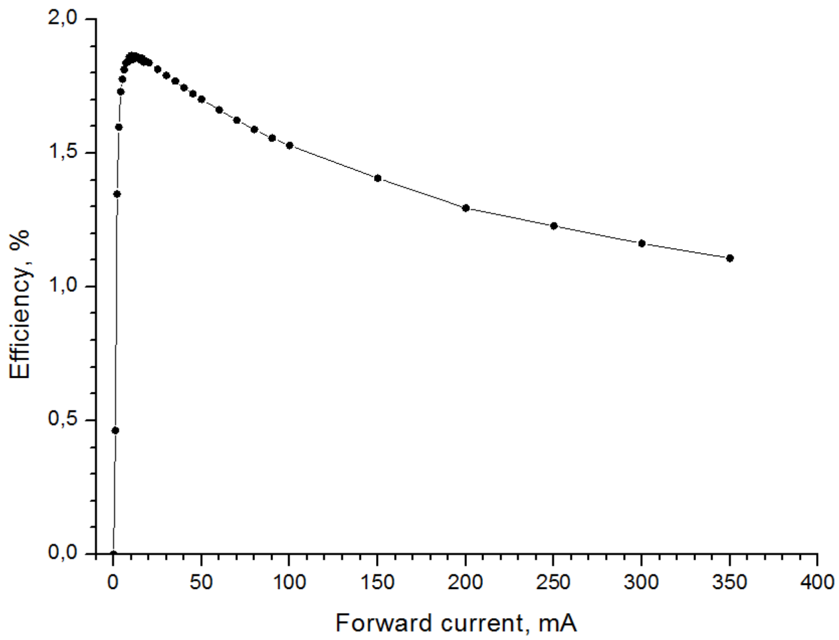


Figure. Energy conversion efficiency vs. current, Nikkiso 285 nm SMD 3535 UV LED.

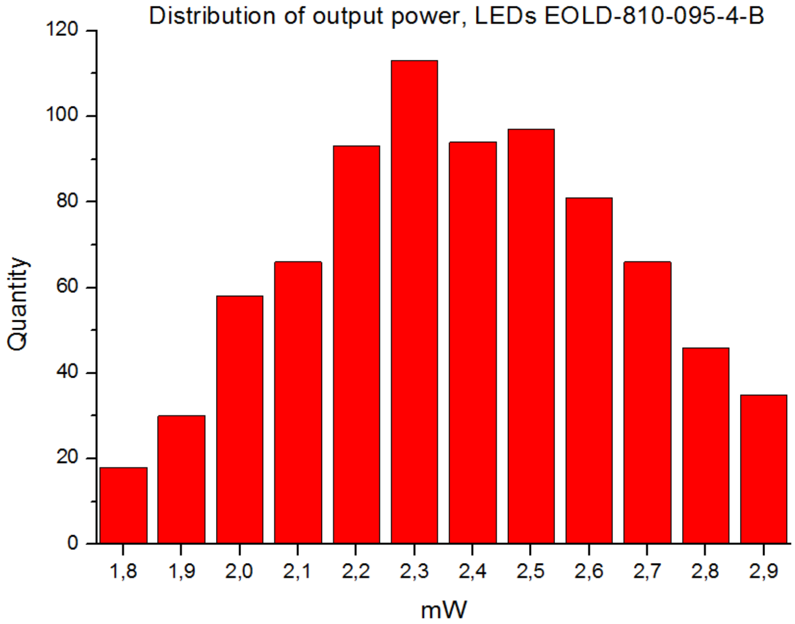
1.9. binning parameters to achieve low parameter spread

Manufacturers often select LEDs (at chip or component level) into bins of certain parameters like:

- peak wavelength, dominant wavelength or colour coordinates,

- optical power, radiant intensity etc.

example, (source: EPIGAP-Optronic GmbH):



1.10. Spatial properties of LEDs

1.10.1. solid angle Ω, in steradian (sr)

describes two-dimensional angular spans in three-dimensional space. The steradian (symbol: sr) is the SI unit of solid angle. The steradian, like the radian, is dimensionless. A steradian is defined as the solid angle subtended at the center of a sphere of radius r by a portion of the surface of the sphere whose area, A, equals r^2.

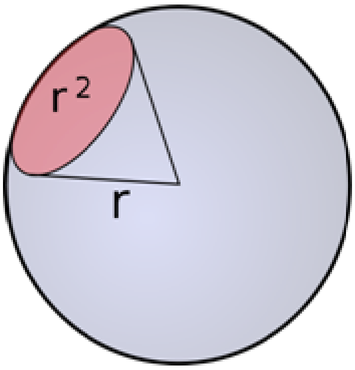
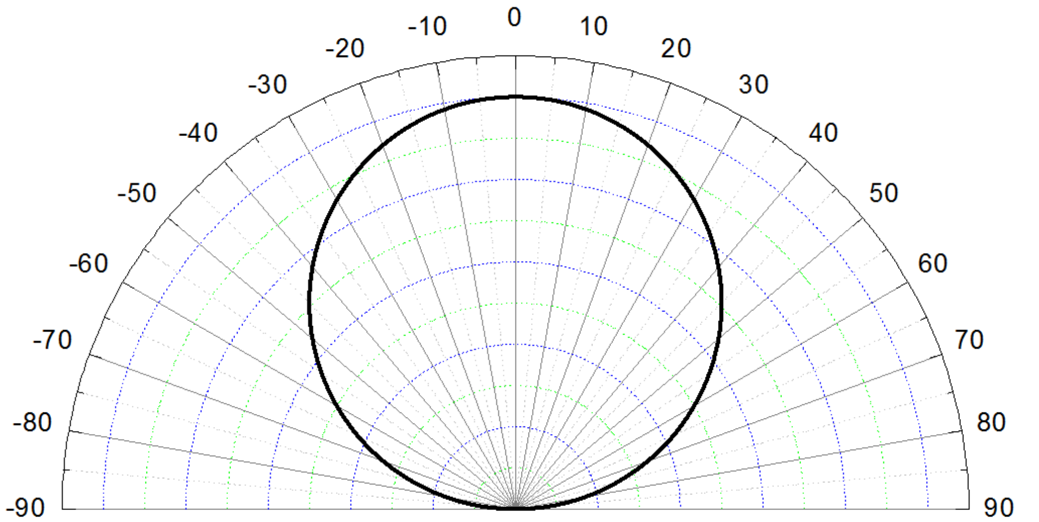


figure: steradian illustration

1.10.1. Far field radiation pattern of an LED
LED is not point source. However, at larger distances (d/D > 10) it can be considered to be a point source. This case is called far field (in contrast to near field where radiation distribution is highly non-uniform). In the far-field range, radiation decreases as the square of distance.

1.10.2. Angle of half intensity (emission angle)

Angle of half intensity, $\varphi_{0.5}$ or $\theta_{0.5}$ is the angle within that the radiant intensity is higher or equal to half of the maximum intensity. For visible LEDs angle of half intensity is sometime called the emission angle. There is residual optical power outside this angle. Typical values of half intensity angles are ±3° to ±60° or even more.



±60 (120) degrees LED. Lambertian distribution is typical for many chips and SMD LEDs.

1.10.3. total included angle

is the angle that includes 90% of the total radiant or luminous flux.

1.10.4. What are typical radiation patterns of LEDs?

Unfocused chips without optics have generally a Lambertian angle distribution, i.e. $\varphi_{0.5}$=120° (±60°). Smaller angles can be achieved using lenses and / or reflectors. For standard 5 mm epoxy packages the smallest available angle is about 6° (±3°). To reduce product nomenclature popular values are 15°, 20°, 30°, 50°, 70°, 90°. Further more stem type 2- or 3-pins LEDs (TO-18, TO-46, TO-39) metal-glass gold plated packages) with epoxy resin lens, glass ball lens or flat windows are available with various emission angles.

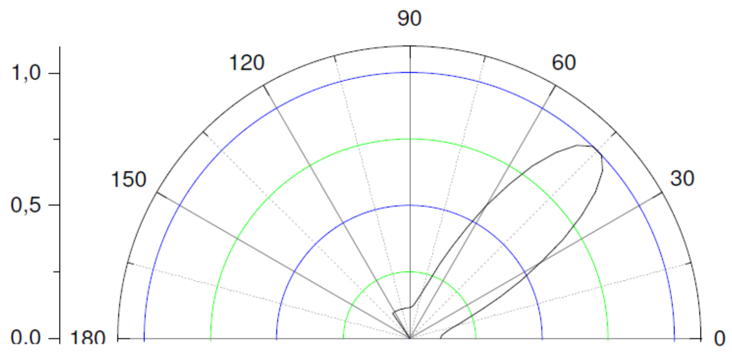
1.10.6. Squint

Squint refers to the angle between mechanical and optical axis.

1.10.6.1. What is required squint?

In some cases the LED package may be designed to create a required squint.


SMD LED 1206 without and with squint. The chip has central or non-central position.



Typical squint radiation pattern (squint angle 45°).

1.10.6.2. What is unwanted squint?

Usually mechanical and optical axises of LEDs are the same. But there might be an unwanted divergence of these axises caused by poor alignment or other circumstances.

This unwanted squint especially appears in narrow-angle and small size LEDs.

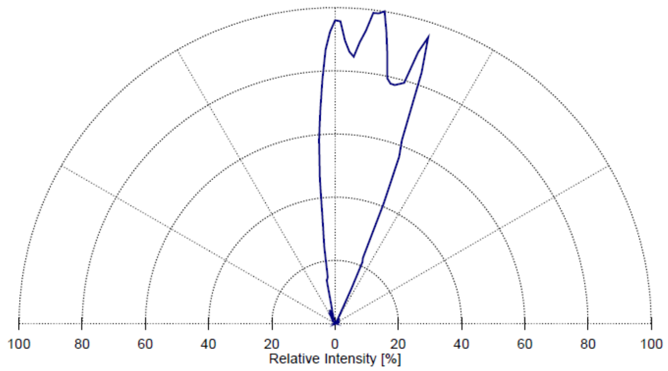


figure: This is a radiation pattern of 3 mm visible LED shows a profound difference between optical and mechanical axis.

1.11. What special LED chip sizes does Epigap offer?

1.11.1. point source LED chips

These are LED chips that have a round and homogeneous emissions area. As other LEDs they do not show speckle formation as laser diodes do. The emissions area of EPIGAP LED point sources can be customized. Since they consume little electrical power point sources are ideal for use in battery-powered devices.

Point source LEDs in the λ range of 630…850 nm with spot diameters from 25 to 200 µm are available from Epigap. Form factors are bare die, TO-can, CoB or other.
link: special chips

Applications:

optical scanning / optical sensors
optical switches
linear & rotary encoders
edge sensing
machine vision / CCD
medical devices, e.g. for blood analysis
fluorescence microscopy
optical instruments
miniature light point in optical sights
focused beam for light barriers
replacement of VCSEL semiconductor lasers (no speckle pattern)

1.11.2. rectangular (not quadratic) LED chips

For some applications rectangular (non-quadratic) LED chips are the preferred form of the light source. Epigap offers such rectangular chips with minimal size of about 300µm in one dimension and length / width relation of up to 1:3.

1.11.3. chip clusters

are semiconductor structures of chips that were not divided (sawed) on wafer level.

Chip clusters (usually 2 x 2) are available from Epigap.

1.11.4. display

LED display chips enable to present numbers, letters and symbols in optical instruments. Each segment is separately addressable. Epigap`s red color (630 nm) GaAsP based chips are well visible at low currents, resulting in extended battery life in portable optical instruments.
link: special chips

1.12. dimming of LEDs
LEDs can be dimmed either

- by adjusting the cw current or

- by using pulse width modulation.

Both ways influence chip temperature, emission spectrum and color coordinates. For details please contact Epigap.

1.13. light output degradation

In normal operation the amount of light produced by a LED will gradually decrease over operational time. The rate of decrease depends on the chip temperature and the current density. LEDs driven at low forward currents at room temperature will degrade slower than LEDs driven at high forward currents and at elevated temperatures. Usually typical degradation data is presented in data sheets.

Light output degradation is caused by stress on the LED chip: mechanical, thermal or electrical. Stress causes defects in the chip to propagate along the planes of the chip's crystalline structure.
These defects in the crystalline structure, called dark line defects, increase the percentage of non-radiative recombination. Designers using LEDs should consider light output degradation over time by adequate degradation margins. This supports LED function over the prospected life time.

Steady State Operating Life of High Humidity Heat		60°C, RH=90%, I_F =20 mA	500 hrs.	0/100
Steady State Operating Life of Low Temperature		Ta=-30°C, I_F=20 mA	1000 hrs.	0/100

1.13.1. What are criteria for judging damage?

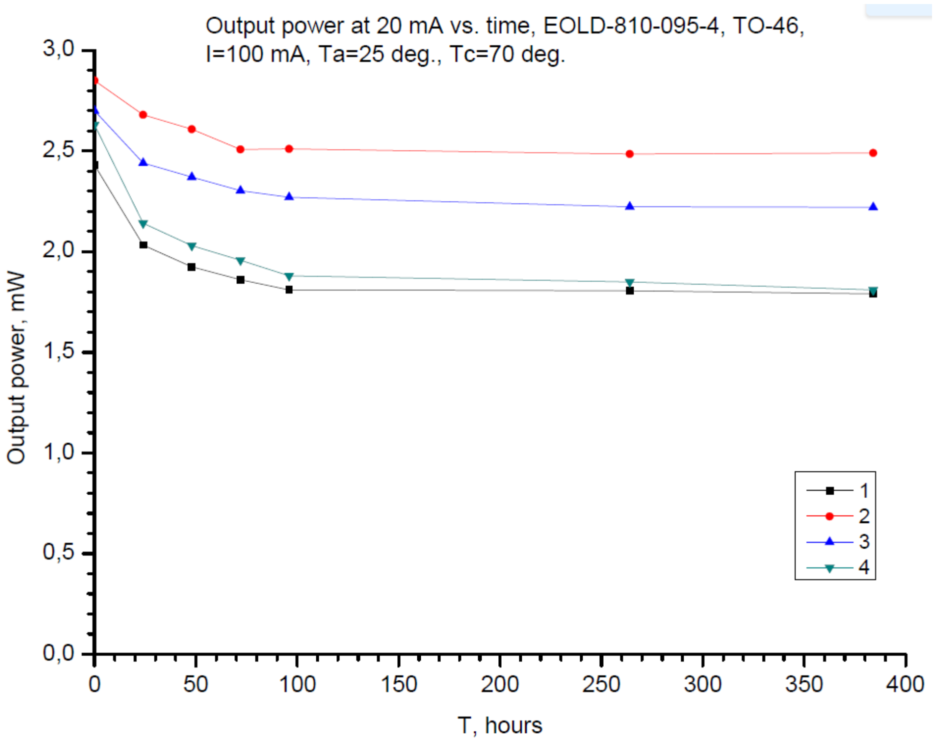
Besides catastrophic damages, there are criteria for judging damage.

Test item	Symbol	Measurement conditions	Judgment criteria	
			Min.	Max.
Forward voltage	VF	I_F=20 mA	-	U.S.L.* x 1.1
Reverse current	I_R	V_R=5 V		U.S.L.* x 2
Luminous intensity	I_V	I_F=20 mA	L.S.L.** x 0.7	
Output optical power	Φ_e	I_F=20 mA	L.S.L.** x 0.5	

*U.S.L. - Upper Standard Level, **L.S.L. - Lower Standard Level

1.13.2. How does the rate of degradation depend on the LED forward current?

Degradation rate depends strongly on the LED forward current. The higher the current, the quicker the degradation. The picture below illustrates this phenomenon.



Degradation test, source: EPIGAP-Optronic GmbH