Technical note

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LED

Contents

LEDs (light-emitting diodes) are opto-semiconductors that convert electrical energy into light energy. LEDs offer the advantages of low cost and a long service life compared to laser diodes.
LEDs are broadly grouped into visible LEDs and invisible LEDs. Visible LEDs are mainly used for display or illumination, where LEDs are used individually without photosensors. Invisible LEDs, however, are mainly used with photosensors such as photodiodes or CMOS image sensors.
In the visible LED category, Hamamatsu provides red LEDs used in combination with photosensors for applications such as optical switches. Hamamatsu red LEDs have high emission power that allows photosensors to generate a large photocurrent when they detect the LED light. In the invisible LED category, Hamamatsu offers near infrared and mid infrared LEDs. These red, near infrared, and mid infrared LEDs are used in a wide range of applications including optical switches, optical communications, analysis, and CMOS image sensor lighting.

Hamamatsu LEDs

Type		Peak emission wavelength	Applications	
Red LED	High output	660 to 700 nm	●Optical switches	●Barcode readers
	Narrow directivity		●Optical switches	
	RC (resonant cavity) type		●Optical fiber communications	
Infrared LED	High output	830 to 945 nm	●Optical switches ●Lighting for near infrared cameras	●Triangulation measurement
	High-speed response		●Optical rangefinders	●Optical fiber communications
	Current confinement type (small light-spot type)		●Optical switches	●Optical fiber communications
	Collimated light		●Encoders	
	Near infrared (1 μm to)	1.2 to 1.55 μm	●Moisture & gas detection	●Optical switches
Mid infrared LED	Mid infrared (3 μm to)	3.3 to 4.3 μm	●Gas detection	

1. Features

- High emission luminance, small product variations

Our LEDs exhibit small variations in luminance between products of the same LED type, which are mostly about -20 to +30%.

- Wide-ranging product lineup

We provide red, near infrared, and mid infrared LEDs created using Hamamatsu unique crystal growth technology and process technology.

- High reliability through meticulous process control

Hamamatsu mainly manufactures LEDs for optical switches, communications, and the like where high reliability is essential (we do not make visible LEDs for display applications). To maintain high reliability we implement meticulous process control. We also offer LEDs for use in vehicles where durability against high temperatures, high humidity, and temperature cycling is essential.

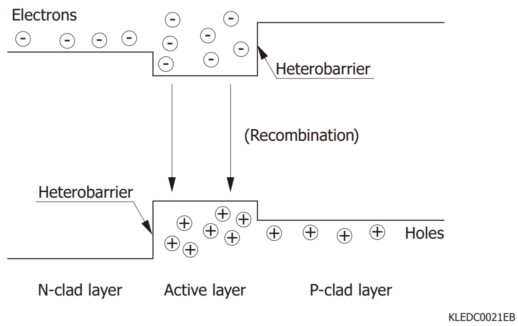
- Custom devices available

Hamamatsu also makes LEDs to custom specifications, including catalog products with partially modified specifications. We are also able to handle production from a relatively small quantity since all processes from wafer growth to final inspection can be carried out in-house.

2. Structure

The LED chips are manufactured starting from an LED wafer containing internal PN junctions, which is then subjected to processes including diffusion and vapor deposition, and is finally diced into chips. First, in the LED wafer, PN junctions are formed by vapor epitaxial growth. These PN junctions can be made from the same material, but using different materials makes it possible to create LEDs with high emission efficiency. For example, the structure in which the GaAs active layer is sandwiched between clad layers of GaAlAs is called double-heterostructure (DH) because both the P-clad layer and N-clad layer are in a heterojunction. In this structure, the injected electrons and holes are confined in a high density state by the heterobarrier [Figure 2-1]. This increases the probability of the electrons and holes to recombine thereby increasing the emission efficiency.

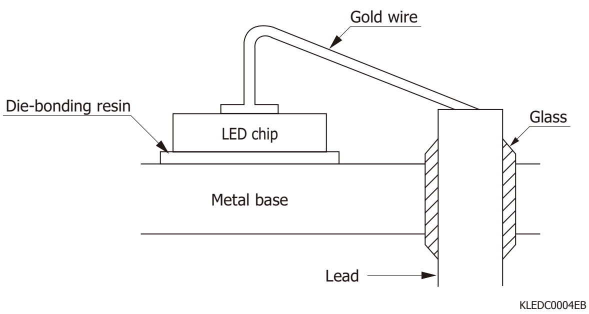
[Figure 2-1] Double-heterostructure



Next, gold electrodes are vapor-deposited on the upper and lower surfaces of the LED wafer and are subjected to a high temperature to form alloys that provide ohmic contacts between the gold and semiconductor. The electrodes on the chip upper surface are then etched away, leaving only the minimum required sections for extracting light with high efficiency.

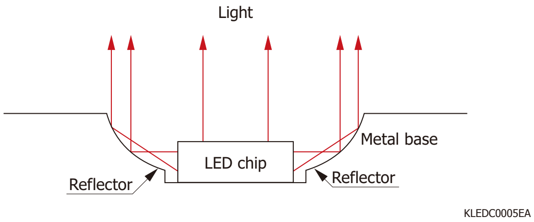
LED chips are usually die-bonded to a gold-plated metal base or a silver-plated lead frame and electrically connected by gold wire to wire leads. For protection, the gold wire is then resin-coated or the package sealed with a cap. Figure 2-2 shows the LED chip mounted on a metal base.

[Figure 2-2] LED chip mounted on metal base



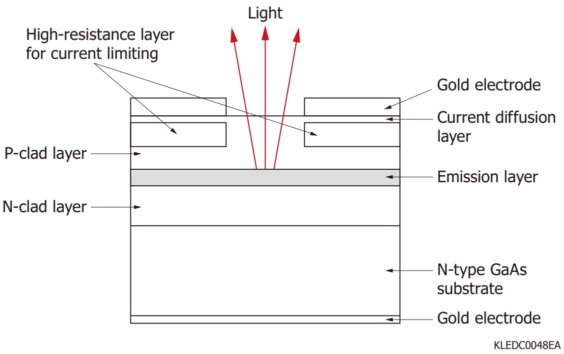
To enhance radiant power, some LEDs use a metal base with a concave area which serves as a reflector, and the LED chip is mounted in that area [Figure 2-3].

[Figure 2-3] Reflector structure



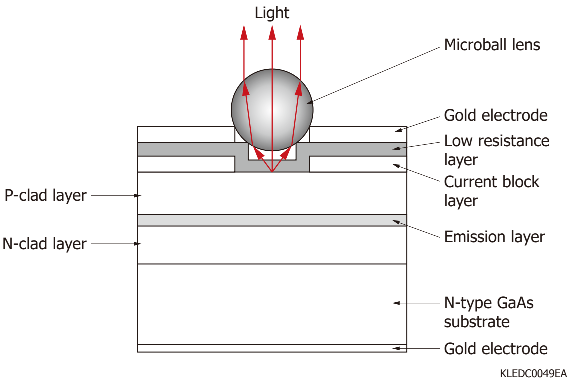
With normal LEDs, the entire chip emits light, but with small light-spot LEDs, the light emission area is limited by running current through a section of the LED chip [Figure 2-4].

[Figure 2-4] Cross section of small light-spot LED



Small light-spot LEDs with microball lens use microball lens to nearly collimate the emitted light to increase the coupling efficiency with optical fiber [Figure 2-5].

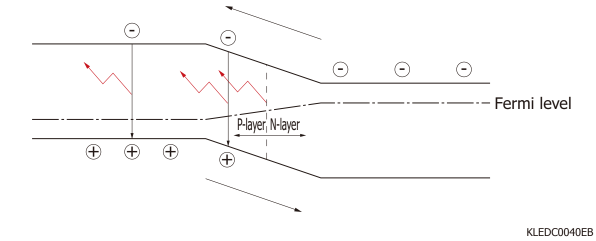
[Figure 2-5] Cross section of small light-spot LED with microball lens



3. Operating principle

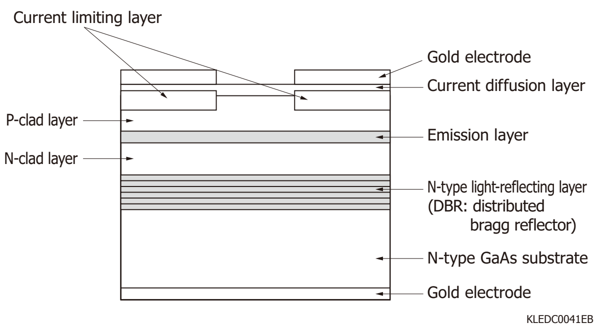
When a forward voltage is applied to an LED, the potential barrier of the PN junction becomes smaller, causing movement of injected minority carriers (electrons in the N-layer, holes in the P-layer) [Figure 3-1]. This movement results in electron-hole recombination which emits light. However, not all carriers recombine to emit light (emission recombination), and a type of recombination not emitting light (non-emission recombination) also occurs. The energy lost by recombination is converted into light during emission recombination but is converted into heat during non-emission recombination.

[Figure 3-1] LED energy levels with forward voltage applied



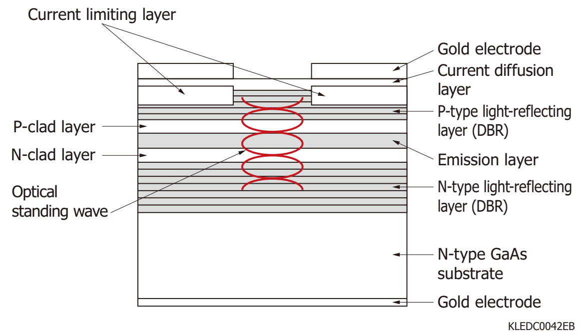
Light generated by electron-hole recombination travels in various directions. Light emitted upward can be extracted from the upper surface of the chip with relatively high efficiency. Light emitted sideways can also be converted to effective light with relatively high efficiency by using a reflector to reflect the light forward. For light emitted downward, if there is a GaAs substrate, light absorption will occur there. In vapor phase epitaxial growth, however, the GaAs substrate cannot be removed because the epitaxial layer is too thin. To cope with this, a light-reflecting layer is formed beneath the emission layer to suppress light absorption in the GaAs substrate [Figure 3-2].

[Figure 3-2] Cross section of LED having light-reflecting layer



When a light-reflecting layer is formed over and under the emission layer, the emitted light reflects repeatedly between the upper and lower light-reflecting layers, causing a weak resonance. This resonance light can be extracted from the upper side of the LED chip by setting the reflectance of the upper light-reflecting layer lower than that of the lower light-reflecting layer. An LED with this structure is called the RC (resonant cavity) type LED. The cross section of an RC type LED is shown in Figure 3-3.

[Figure 3-3] Cross section of RC type LED

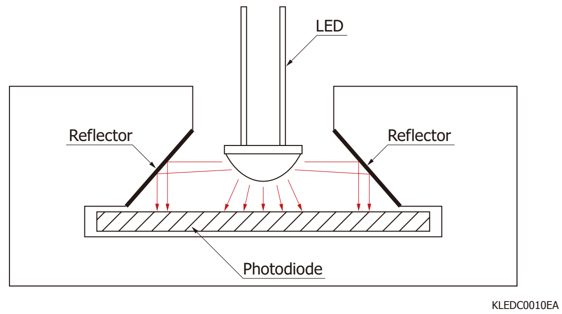


4. Characteristics

4 - 1 Radiant flux (total light amount)

Radiant flux is the amount of light obtained by measuring all light emitted from an LED. Radiant flux is generally measured using an integrating sphere, but a simple measurement can be made by using a tool with a reflector (mirror).

[Figure 4-1] Radiant flux measurement method



Light emitted from an LED is not a single wavelength, so the amount of light of each wavelength must be measured and integrated to obtain an exact radiant flux value. In most cases, however, the photodiode photocurrent is measured and converted into a light level based on the photodiode spectral response at the peak emission wavelength. This method is close to that of actual LED usage, so measuring the radiant flux by this method does not cause any significant problems.

4 - 2 Radiant intensity

Radiant intensity is a measure for indicating the intensity of light emerging from the front of the LED. This is obtained by converting results measured at a small solid angle into a value per unit solid angle, and is expressed in W/sr units. In the case of small solid angles, if we let the photodiode photosensitive area be “S,” and the distance from the LED to the photodiode be “r,” the solid angle “ω” can be expressed by equation (1).

$$\omega = S/r^2 \cdots\cdots\cdots\cdots (1)$$

For example, when a photodiode with an photosensitive area of ϕ0.12 cm is placed at a position 30 cm away from the LED, the solid angle ω will be nearly equal to 1.26×10^{-5} sr. If the measured light level is 1 μW, then the radiant intensity Ie is given by equation (2).

$$Ie = \frac{1 \times 10^{-6}\ \mathrm{W}}{1.26 \times 10^{-5}\ \mathrm{sr}} \approx 80\ \mathrm{mW/sr} \cdots\cdots\cdots\cdots (2)$$

Radiant intensity is useful for indicating the optical power that is measured in front of an LED with lens. Radiant intensity is the power per unit solid angle, and so is not dependent on the distance. However, if the photodiode is close to the LED, the position of the virtual point light source and that of the LED chip will be different, which causes deviation from this relationship.

4 - 3 Irradiance

As with radiant intensity, irradiance is a measure for indicating the intensity of light emerging from the front of an LED. Irradiance is obtained by converting the results measured in a small area into a value per unit area and is expressed in units of W/cm^2.
For example, when a photodiode with an photosensitive area of ϕ0.12 cm is placed at a position 30 cm away from the LED and the measured light level is 1 μW, then the irradiance Ee is expressed by equation (3) using the photodiode photosensitive area which is 0.011 cm^2.

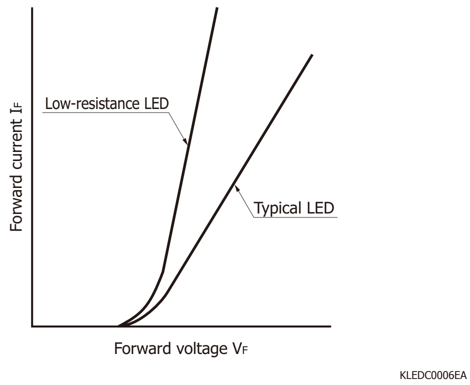
$$Ee = \frac{1\ \mu W}{0.011\ cm^2} = 91\ \mu W/cm^2 \cdots\cdots\cdots\cdots (3)$$

Irradiance is the power per unit area and so is inversely proportional to the square of the distance from the LED. But this inversely proportional relationship is lost if the photodiode is too close to the LED because the LED emission section is not a point light source.
The irradiance values listed in our datasheets are measured by placing a photodiode with an photosensitive area of 1 × 1 cm at a position 2 cm away from the LED. These values can be used as a guide for finding the level of light passing through an external light projection lens.

4 - 4 Forward current vs. forward voltage characteristics

LEDs have forward current vs. forward voltage characteristics similar to those of rectifier diodes. The characteristic curves of individual LED types differ depending on the element structure and other factors [Figure 4-2].

[Figure 4-2] Forward current vs. forward voltage

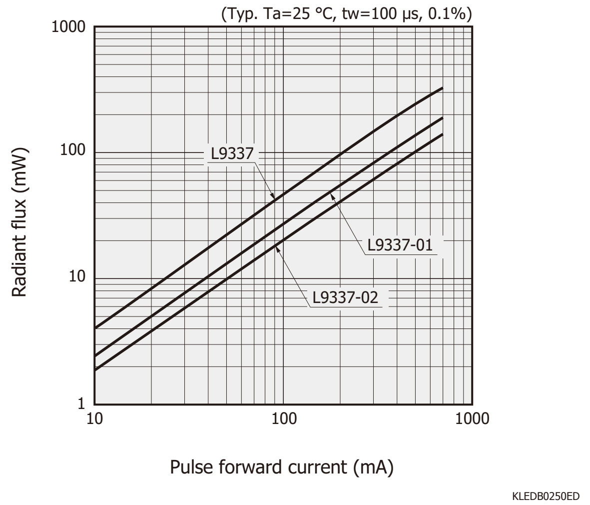


Compared to an ordinary LED, the low-resistance LED requires a lower forward voltage (VF) to allow the same amount of forward current to flow. The term "resistance" here is different from the word used in the normal sense; it denotes the slope (differential resistance) of the tangent line for the special forward current shown in Figure 4-2.
In general, using an LED with a lower forward voltage allows easier circuit design. An LED with a higher forward voltage will consume more power even when operated at the same current value. This will cause a corresponding temperature rise in the LED, resulting in detrimental effects such as lower output power, shifts in the peak emission wavelength, and LED degradation.

4 - 5 Radiant flux vs. forward current characteristics

The radiant flux vs. forward current characteristics show a near straight line. So if the radiant flux is measured at a certain current value, the approximate radiant flux for a different current value can be easily estimated. However, if the temperature of the emission section increases due to the ambient temperature and heat generated from the LED itself, then the radiant flux decreases and saturation can be observed in the characteristic graph. In pulsed operation, the saturation state varies according to the pulse width and duty ratio.

[Figure 4-3] Radiant flux vs. pulse forward current (L9337 series)



4 - 6 Directivity

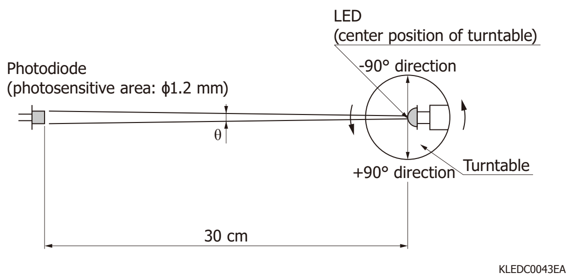
Directivity indicates to what extent the light emitted from an LED spreads. At Hamamatsu, this directivity is measured with the following procedure using the measuring device constructed as shown in Figure 4-4.

① An LED is set on the turntable in the dark box. (position of emission area: center of turntable)

② The turntable is rotated through 180° to make the front of the LED first face -90°, and then make it face +90°.

③ Light emitted from the LED is detected with the photodiode while the turntable is rotated.

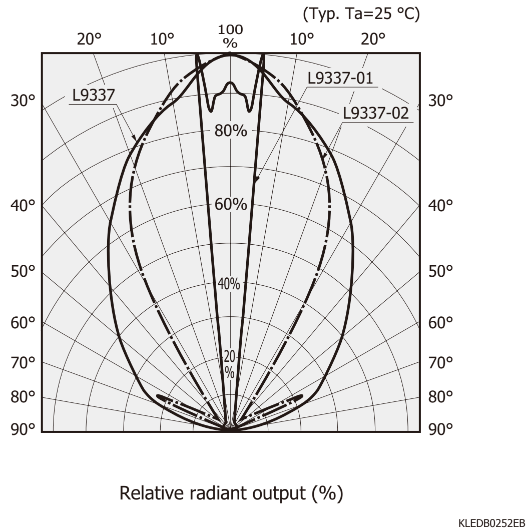
[Figure 4-4] Directivity measurement setup (inside dark box)



Directivity is expressed as a percentage of the peak value and plotted on a graph. To indicate the directivity numerically, a full width at half maximum or FWHM (angle at which the light output is half the maximum output) is used. Since directivity is normally symmetrical, the full width at half maximum is represented as a plus or minus value like ±10°.

To achieve high resolution in the directivity measurement, the angle (θ in Figure 4-4) from the LED toward the photodiode photosensitive area must be small. So the distance from the LED to the photodiode is set as long as needed, and the photodiode used must have a small photosensitive area. Radiant intensity can be obtained from the photodiode output when the turntable is positioned at 0°.

[Figure 4-5] Directivity (L9337 series)

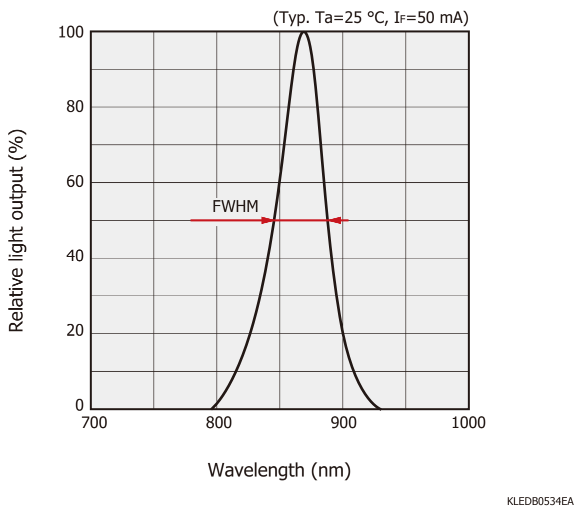


4 - 7 Emission spectrum

An LED's peak emission wavelength is determined by the epitaxial wafer material. It is approx. 940 nm for GaAs and 660 to 900 nm for GaAlAs (depending on the Al mixed crystal ratio).

Unlike laser diodes, LED emits light over a wide spectral range. The extent to which the emitted spectrum spreads is expressed in a full width at half maximum (FWHM) [Figure 4-6]. LED emission spectra vary with the ambient temperature and the heat while conducting power, and shift to the long wavelength side as the temperature increases.

[Figure 4-6] Emission spectrum (L9337 series)



4 - 8 Response speed and cutoff frequency

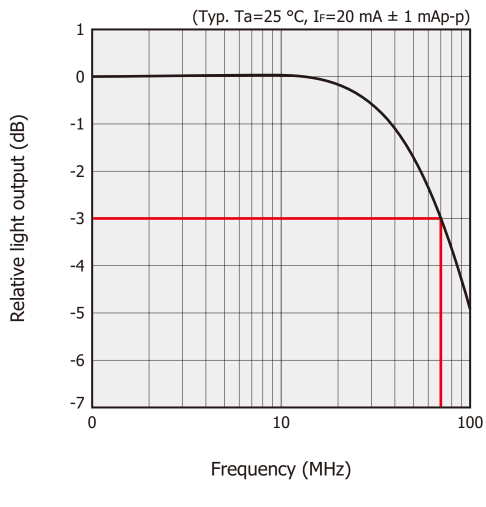
An LED emits light at a given response speed which causes a delay in the light emission waveform relative to the input current waveform. The LED response speed is expressed in terms of rise time and fall time of the light emission waveform produced when a square-wave

pulse current flows through the LED. This rise time is the time required for the level to rise from 10% to 90% of the peak of the light emission waveform, and the fall time is the time required to fall from 90% to 10%.
The cutoff frequency also indicates the LED time response. When sine waves in DC current flowing through an LED reach a high frequency, the LED emission response cannot follow up on this change so the amplitude of the emission waveform becomes small. The cutoff frequency is defined as the frequency at which the amplitude of the emission waveform decreases to 1/2 (-3 dB) of the initial level [Figure 4-7]. The cutoff frequency (fc) can be empirically approximated by equation (4) if the rise time (tr) and fall time (tf) are equal.

$$fc = \frac{C}{tr} \quad \cdots\cdots\cdots\cdots \quad (4)$$

C: constant (0.35 to 0.4)

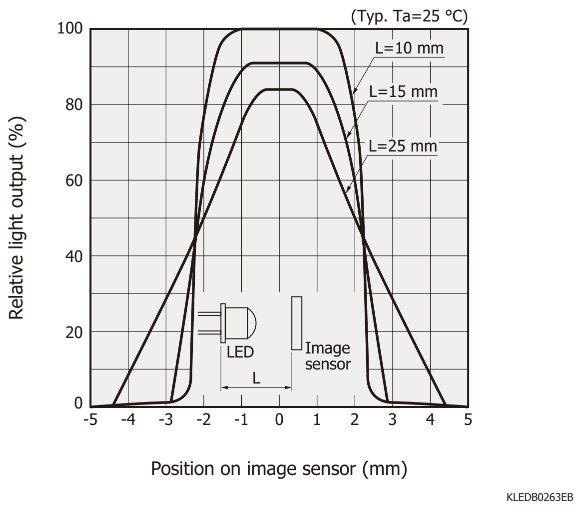
[Figure 4-7] Frequency characteristics (L10762)



4 - 9 Light intensity distribution of collimated LEDs

Light intensity distribution is an important characteristic for collimated LEDs used in optical transmissive encoders and the like. The light intensity distribution is measured by installing an image sensor at a position facing the LED and emitting the LED [Figure 4-8]. In some cases, a slit is provided between the LED and image sensor to make the measurement.

[Figure 4-8] Light intensity distribution (L11913)



5. How to use

5 - 1 DC drive

The most common method for using LEDs in applications such as optical switches is to provide a constant forward current flow. In this method, care should be taken not to allow the forward current to exceed its absolute maximum rating for the LED. If the ambient temperature of the LED is likely to be high, then allowable forward current versus the ambient temperature characteristics must be taken into account.

For an LED with low tolerance to electro-static discharge (ESD), a protection Zener diode needs to be connected externally so that excessive voltage is not applied to the LED.

[Figure 5-1] Example of DC drive circuit

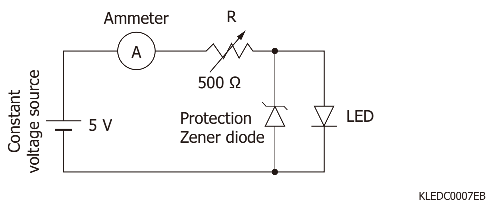
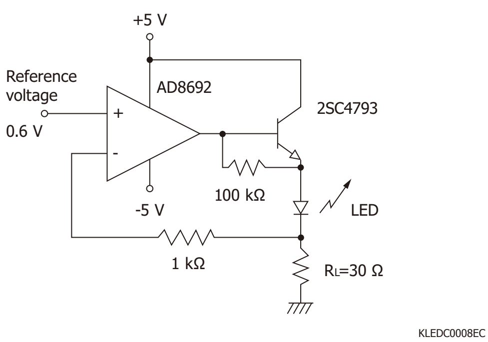


Figure 5-1 shows the simplest circuit example. To make a constant current of 20 mA flow in this circuit, first set the variable resistor R to a maximum value and then apply the voltage. Next, gradually reduce the resistance of the variable resistor until the current reaches 20 mA while watching the ammeter. If not using a variable resistor, then the resistance value should be calculated. For example, if the LED forward voltage is 1.4 V while the forward current is 20 mA, then the resistance R is given by: R = (5.0 V - 1.4 V)/0.02 A = 180 Ω. So a 180 Ω resistor should be used here.

In the circuit shown in Figure 5-1, the forward current varies slightly according to fluctuations in the LED forward voltage. To prevent these fluctuations, a constant current circuit using an op amp is useful. Figure 5-2 shows a simple constant current circuit utilizing an op amp.

[Figure 5-2] Example of constant current circuit using op amp

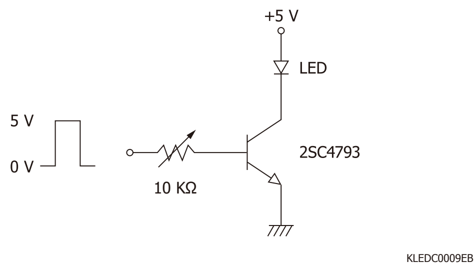


In Figure 5-2, a reference voltage of 0.6 V is applied to the normal-phase input terminal (+) of the op amp and the potential of the reverse-phase input terminal (-) becomes nearly equal to this reference voltage potential. So the voltage drop across resistance R_L is 0.6 V, and a current of 20 mA (0.6/30 = 0.02 A) flows through the LED. The desired LED drive current can be set by changing the R_L value.

5 - 2 Pulse drive

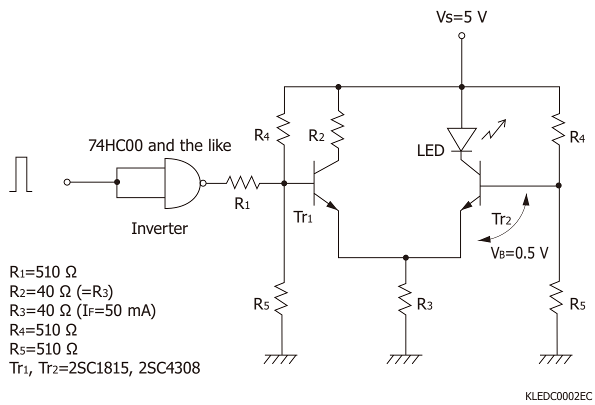
The simplest pulse drive method is to supply a pulse generator output directly to both ends of the LED. However, the current capacity is usually insufficient in this method, so a transistor as shown in Figure 5-3 must be used. During pulse drive, the current value must never exceed the absolute maximum ratings.

[Figure 5-3] Example of pulse drive circuit



When driving the LED in high-speed pulse mode, a high-speed drive circuit is required. Figure 5-4 shows a high-speed pulse drive circuit.

[Figure 5-4] Example of high-speed pulse drive circuit



In Figure 5-4, the LED turns on when the input is at the high level. The forward current (I_F) which flows through the LED can be given by: $I_F = (V_S/2 - V_B)/R_3$ [with this circuit example, $I_F = (5/2 - 0.5)/40 = 0.05$ A]. The response speed of this circuit is determined by the response speed of Tr_1 and Tr_2. It will be about 20 MHz if 2SC1815 is used and about 100 MHz if 2SC4308 is used.

5 - 3 Degradation

When an LED is used for long periods of time, its performance degrades. Degradation usually appears as a decrease in output power or fluctuations in the forward voltage. These degradations are thought to be due to crystal dislocations and shifts caused by heat generation in the emission section. These can be observed as dark lines or dark spots.
Degradation also occurs from external stress. If the LED is driven with stress applied to the LED chip, its performance will degrade drastically. This stress might also be caused by mechanical distortion on the package, so use plenty of caution when mounting the LED.

Method for calculating the degradation rate

In general, the LED light output (P) decreases exponentially with operating time as expressed in equation (5).

$$P = Po \times \exp(-\beta t) \cdots\cdots\cdots\cdots (5)$$

Po : initial light output
β : degradation rate
t : operating time

The degradation rate β in equation (5) depends on the element materials, structure, and operating conditions, etc. and is usually assumed as shown in equation (6).

$$\beta = \beta o \times I_F \times \exp(-Ea/k\,Tj) \cdots\cdots\cdots\cdots (6)$$

βo : degradation constant (inherent to LED)
I_F : operating current [A]
Ea : activation energy [eV]
k : Boltzmann's constant [eV/K]
Tj : temperature of light-emitting layer [K]

In equation (6), I_F is added to the Arrhenius equation which relates to the emission layer temperature, based on the view that dislocations and shifts in the crystal are caused not only by lattice vibrations due to temperature but also by the energy from non-emission recombination.
The emitting layer temperature (Tj) is expressed by equation (7).

$$Tj = (Rth \times I_F \times V_F) + Ta \cdots\cdots\cdots\cdots (7)$$

Rth: thermal resistance [°C/W]
V_F : forward voltage [V]
Ta : ambient temperature [K]

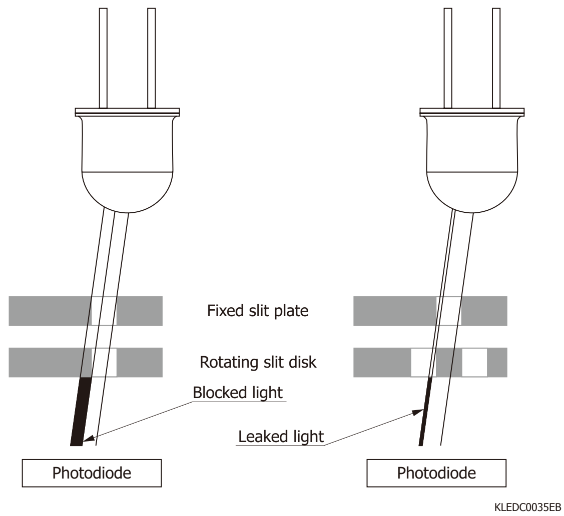
By using equations (5), (6), and (7), the degradation rate under other conditions can be figured out from the life test data measured under certain conditions. For example, if we have life test data measured at 50 mA DC for up to 3000 hours, then β can be found from equation (5). Based on this β and equation (5), the extent of degradation after 3000 hours of operation under the same conditions can be estimated. To calculate the life data of the same LED operated under different conditions, βo should be obtained by substituting Tj found from equation (7) into equation (6) together with β obtained previously. After βo is obtained, substituting the objective test conditions into equation (6) gives the degradation rate β.
The activation energy (Ea) usually used is 0.5 to 0.8 eV, and the thermal resistance ranges from about 300 to 350 °C/W for TO-18 and TO-46 packages.
Equation (6) takes only the degradation from heat into account and does not give any consideration to stress degradation and the mode of breaking that might occur if the specified rating is exceeded. Calculation results from equation (6) should therefore be used only as a reference. These are unlikely to match the actual degradation particularly at low temperatures where stress degradation cannot be ignored.

6. Applications

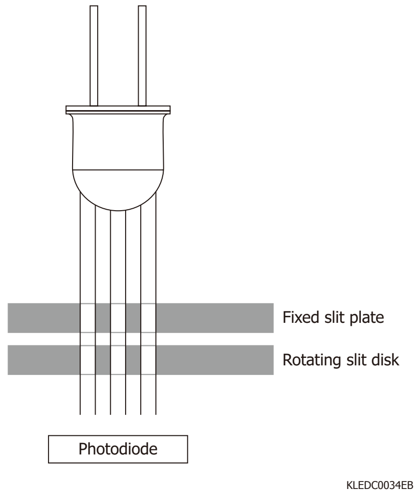
6 - 1 Encoders

To meet FA (factory automation) equipment demands for high-speed and high-precision nano-level control, high-resolution rotary encoders are now being produced that are capable of angular detection down to 36 millionths of a single rotation. A rotary encoder uses a fixed slit plate and a rotating slit disk, both with slits formed at a fine pitch. The passage and blockage of LED light created by the relative movements of the slits are detected with photodiodes to find the angle. Such photodiodes are positioned in complex patterns for high-precision detection, so the LED must illuminate the photodiodes uniformly.
If poorly collimated light is used, various problems arise. For example, a portion of light is blocked at positions where the light should completely pass through slits [left drawing in Figure 6-1]. This lowers the signal amplitude so detection performance drops. Another problem is that light leakage occurs at positions where light through a rotating slit should be blocked by the fixed slit plate [right drawing in Figure 6-1].
To prevent these problems, high-precision encoders must use a “collimated LED” that emits collimated light uniformly with small convergence and dispersion. Hamamatsu provides two types of collimated LEDs: (1) a current confinement type with high parallelism and a small emission spot and (2) a highly reliable type that achieves high parallelism by optimizing the lens shape without using a current confinement structure.

[Figure 6-1] Concept drawing when poorly collimated LED is used



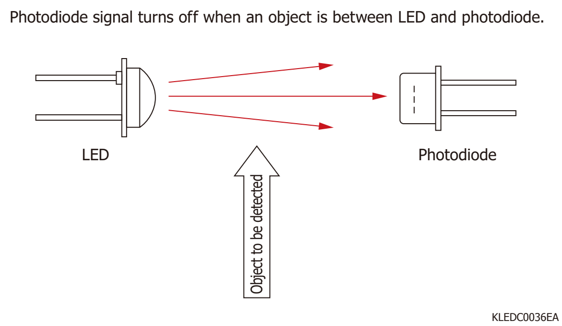
[Figure 6-2] Concept drawing when collimated LED is used



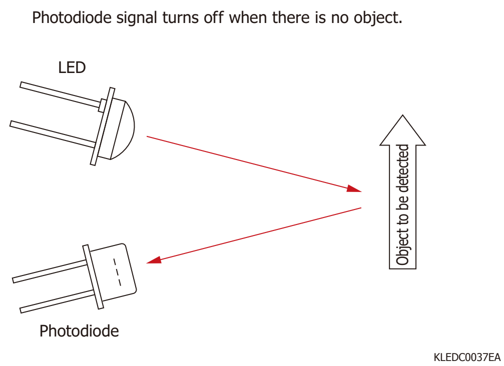
6 - 2 Optical switches

Optical switches are used for detecting the presence or absence of objects without making direct contact with them. In a transmission type optical switch, an LED and a photodiode are arranged facing each other across the path of the object, and the photodiode detects an object when it interrupts the LED light. In a reflective type optical switch, an LED and a photodiode are arranged on the same side, and the photodiode detects an object when it reflects the LED light back to the photodiode.

[Figure 6-3] Transmission type optical switch



[Figure 6-4] Reflective type optical switch

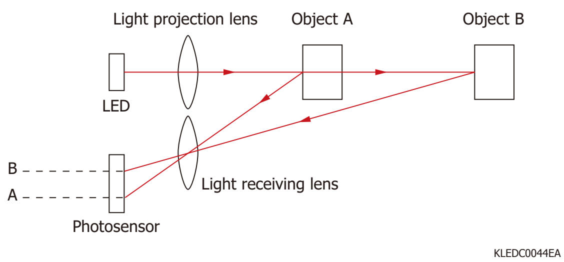


In optical switch applications, red LEDs are often used to make the optical axis easy to align or to indicate the sensing status. The “brightness” visible to the human eye and the “light output” measured with a photodiode might not always match each other. So Hamamatsu provides red LEDs that emit light with 670 nm wavelength which is relatively easy to see and also delivers a large light output.

Near infrared LEDs with a large output are used in many fields including security applications requiring invisible light. When used with a large light projection lens, these LEDs can emit a light beam more than 100 meters. Hamamatsu also provides LEDs using a reflector structure [Figure 2-3] that also makes effective use of light emitted from the side of the chip, allowing a large amount of light into the light projection lens (incident angle: approx. 60°).

Optical switches that contain distance information are increasingly being used. This type of optical switch uses a PSD, two-element photodiode, or the like that detects the position of a light spot, in order to detect an object if it enters a particular distance range. In this case, no detection error will occur even if an object passes through the back of the detection area.

[Figure 6-5] Optical switch system holding distance information



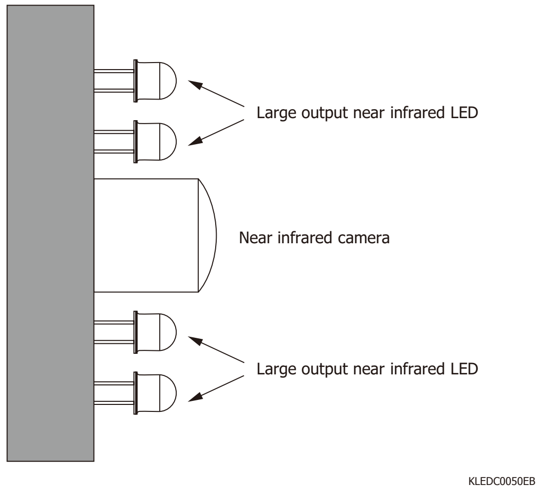
6 - 3 Light sources for object detection

LEDs are also used in recent years as light sources for grain sorting machines and the like. Though heat is emitted from an LED during operation, it is small compared to that from incandescent lamps so LED heat has almost no effect on the grains during sorting.

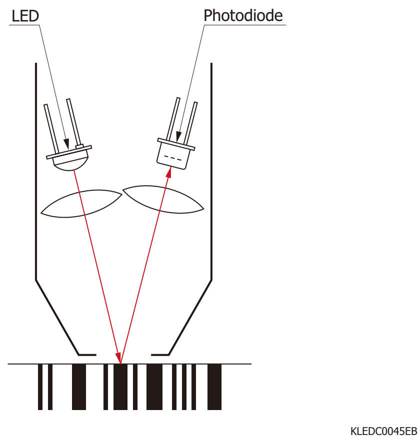
In addition, near infrared LEDs with large output are used as light sources for near infrared camera imaging. These LEDs are arranged in a ring around the camera.

Contact type barcode readers mainly use multiple red LEDs. Pen type barcode readers use a single set consisting of an LED and photodiode.

[Figure 6-6] Lighting for infrared camera imaging

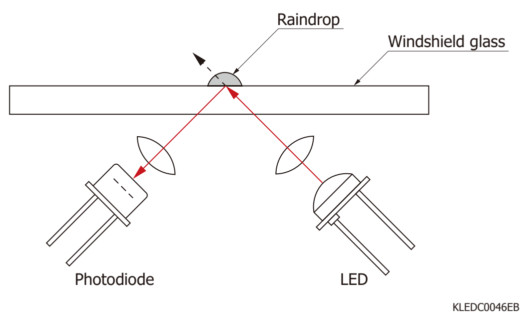


[Figure 6-7] Barcode reader (pen type)



LEDs are also used in raindrop sensors for automobile windshield wipers. In these sensors, a photodiode detects LED light reflecting back from the windshield glass. If a raindrop lands on the surface of the windshield, the light reflectance of the windshield glass will decrease, causing the light level on the photodiode to lower. In this way, the amount of rain can be detected.

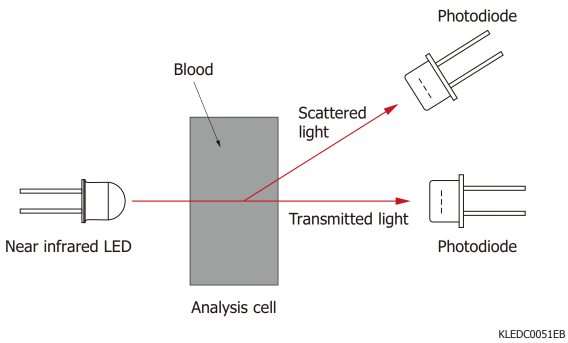
[Figure 6-8] Raindrop sensor



6 - 4 Blood analysis

Blood analysis can be performed by applying light from a near infrared LED to an analysis cell containing blood and detecting the transmitted light and scattered light with a photodiode.

[Figure 6-9] Blood analysis



6 - 5 Distance measurement

LEDs are also used in optical rangefinders that make use of a phase difference to measure distance. Optical rangefinders employ a principle that measures the distance by means of the phase difference that occurs while light travels to and returns from the target point. High-speed response LEDs must be used since high-speed modulation is required to increase the distance measurement accuracy.

6 - 6 Optical communications

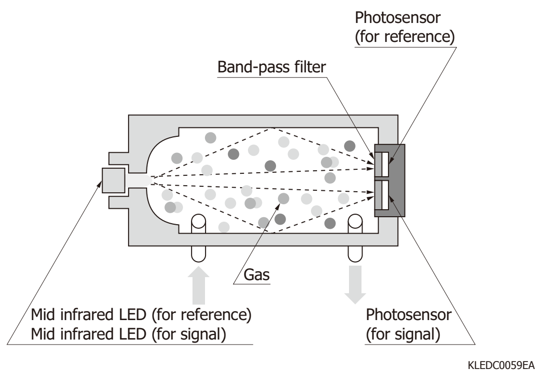
Hamamatsu high-speed and high-power LEDs are used for POF (plastic optical fiber) communications, and FSO (free space optics).

6 - 7 Gas measurement

The mid infrared region contains absorption wavelengths unique to various molecules and is called the "molecular fingerprint region." Because of this, a mid infrared light source and photosensor can be used to perform gas analysis and measurements. Hamamatsu provides three types of mid infrared LEDs with peak emission wavelengths of 3.3 μm, 3.9 μm, and 4.3 μm for use as mid infrared light sources that are compact, high speed, low power consuming, long life, and easy to use.

The principle of gas measurement using a mid infrared LED and photosensor is shown [Figure 6-10]. When the gas to be measured enters the chamber, the light from the mid infrared LED (for signal) is absorbed by the gas and attenuates and incident on the photosensor (for signal). In addition, from the mid infrared LED (for reference), light with a wavelength not absorbed by the gas is incident on the photosensor (for reference). The gas concentration is measured based on the changes in the output ratio of the photosensor (for signal) and photosensor (for reference).

[Figure 6-10] Principle of gas measurement



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