Comparative Study of Diodes and their Optical Performance

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Abstract

In this paper, the basis of optical performance of diodes have been compared. A laser diode (LD) operates based on stimulated emission and emits coherent light. The performance of the light emitting diode (LED) is also based on spontaneous emission and emits incoherent light with different wavelengths. On the other hand, the optical performance of superluminescent light emitting diode (SLED) is based on amplified spontaneous emission. Experimental results have shown that the LD has a thin optical spectrum, and the LED and SLED have a wide optical spectrum. Also, the output optical power of LED and SLED is medium, and the output power of LD is high. The wavelength of the emitted light of each diode depends on the energy bandgap of the semiconductor material that makes that diode. The highest internal quantum efficiency of LEDs, which is achieved at low current densities, is greater than 80% and for blue light-emitting diodes 450 nm.

Keywords: optical performance, diode, stimulated and Spontaneous emission, quantum efficiency

1. Introduction

A diode is an electronic component that passes the electric current in one direction and shows a very high resistance to the current passing in the opposite direction. The diode is made by connecting n and p type semiconductors. When n-type and p-type semiconductor crystals are connected, the free electrons of the n-type semiconductor, which are located near the p-n junction, penetrate into the p region and combine with the holes of the p-type semiconductor. In this way, holes are destroyed and free electrons become valence electrons. With passing of large number of electrons through the junction of semiconductors, a large amount of positive and negative ions are created at the junction. These ions are stable in the crystals, so at the bonding site, arise a null region where there are no carriers of electrical conductivity, i.e., electrons and holes. This null region is also called the barrier region. The electric field created by the positive and negative ions in the null region opposes the passage of free electrons through the junction. When the created field reaches a level that prevents the passage of electrons from the junction, the equilibrium state is created and in this way, a crystal diode is made. The voltage created in the null region is called the barrier potential.

Electrically, by creating the voltage in the direct direction, a diode conducts current and is ready to work. The voltage value that causes the diode to start conducting electric current is called the threshold voltage. But when the reverse voltage is connected to the diode, no current flows through it, except for a very small current known as leakage current, which is around a few microamperes or even less. The amount of leakage current in diodes with new technology is practically zero. But the important point is that all diodes have a threshold for the maximum reverse voltage, if the reverse voltage exceeds it, the diode burns and passes the current in the reverse direction. This threshold voltage is called diode breakdown.

If the positive pole of the power supply is connected to the p-type semiconductor and its negative pole is connected to the n-type semiconductor, the diode is placed in direct bias mode. When the electric field caused by the power supply neutralizes the electric field of the barrier potential, the null region and the barrier potential are destroyed, and the electrons of the n crystal are driven to the bonding site. These electrons enter the p-type crystal and become valence electrons as a result of combining with holes. The valence electrons go from one cavity to another until they reach the end of the crystal and finally the positive pole of the power supply. In the direct bias of the diode, if we gradually increase the voltage across the diode from zero, at first a small current will pass through the circuit. As soon as the diode voltage reaches the contact voltage of the p-n junction, the current starts to increase.

In the reverse bias mode, electrons from the negative pole of the power supply enter the p-type semiconductor and combine with the holes adjacent to the null region, thus the width of the null region in the p-type semiconductor increase. Also, in the n-type semiconductor, the electrons around the null region are attracted to the positive pole of the power supply, and those regions are depleted of electrons, and in this way, the width of the null region increases in the n-type semiconductor. As the null region increases, the barrier potential also increases, and this increase continues until the barrier potential equals the power supply voltage, and after that, the width of the null region remains constant. It should be noted that in the reverse bias of the diode, a very weak current passes through the diode. The direction of this current is from the cathode side to the anode side. This current is known as diode reverse saturation current. The amount of reverse saturation current of the diode depends on the ambient temperature, and after reaching the saturation of the reverse current of the diode, increasing the reverse voltage does not affect its value.

2. Carrier Transfer

The flow of electric current in semiconductors is mainly dominated by the drift and diffusion of electrons and holes [1]. Semiconductor component simulation softwares mainly use the drift-diffusion model to calculate the flow of electrons and holes. The drift current is created by an electric field, which is proportional to the conductivity of electrons ($\sigma_n = q\mu_n n$) and holes ($\sigma_p = q\mu_p p$). Also, Diffusion current is obtained by the concentration gradient of electrons (∇n) and holes (∇p), which is proportional to the diffusion coefficients D_n and D_p, respectively. For the same semiconductors, the total current density of electrons and holes is written as follows:

$$\vec{j}_n = q\mu_n n\vec{F} + qD_n \nabla n \quad (1)$$

$$\vec{j}_p = q\mu_p p\vec{F} + qD_p \nabla p \quad (2)$$

Temporal changes in carrier concentration must be accompanied by a spatial change in current flow ($\nabla\vec{j}$) and/or by generation (G rate) or recombination (R rate) of electron-hole pairs. This relationship is expressed by continuity equations:

$$q\frac{\partial n}{\partial t} = \nabla.\vec{j}_n - q(R-G) \quad (3)$$

$$q\frac{\partial p}{\partial t} = -\nabla.\vec{j}_p - q(R-G) \quad (4)$$

Finally, the electric field is affected by the charge distribution, which includes moving (n, p) and fixed charges (impure ions, p_D, n_A). This ratio is expressed by the Poisson equation:

$$\nabla.(\varepsilon_0 \varepsilon_{st} \vec{F}) = q(p - n + p_D - n_A) \quad (5)$$

This set of equations provides the drift-diffusion model for the electrical behavior of semiconductor devices.

Carrier transfer in semiconductors can also be expressed by the thermionic model [2]. The thermionic model, assuming the Fermi-Dirac carrier distribution in each part of a certain region, describes the carrier transfer with analytical formulas that only depend on the carrier temperature, density and band cross section. This model can be combined with the drift-diffusion model where it is used as a boundary condition between adjacent drift-diffusion regions. The recombination rate R in equations (3) and (4) includes different physical mechanisms. In order for electrons to fall from the conduction band to the valence band, they need to transfer their excess energy to other particles (electrons, phonons, photons). The main mechanisms can be seen in Figure 1. These mechanisms are radiative (emission of photon) or non-radiative (without emission of photon).

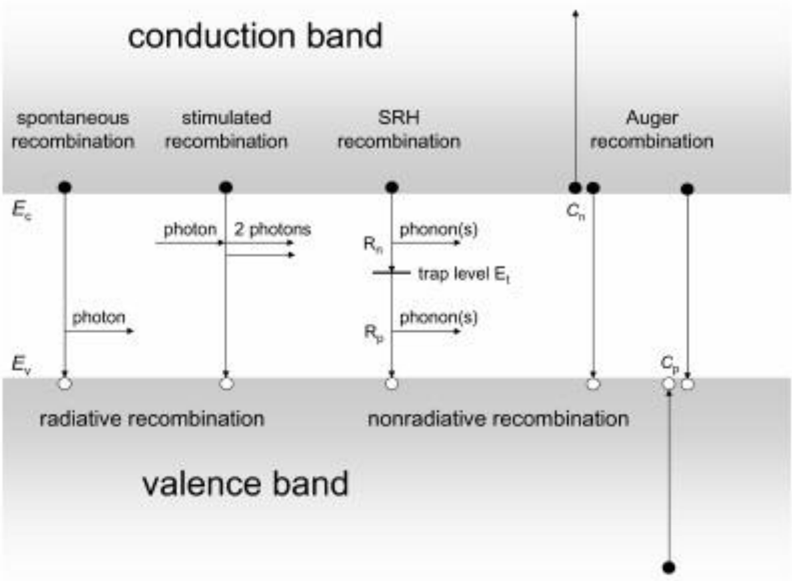

Fig. 1. The main mechanisms of electron-hole recombination in semiconductors [1].

Radiative recombination occurs when the electron in the conduction band recombines with the hole in the valence band and the produced excess energy is emitted as a photon. Photon production by radiative recombination can be done as spontaneous or stimulate. In bulk layers, the spontaneous emission rate of photons is often characterized by the material coefficient B and is written as follows:

$$R_{spon} = B(np - n_0 p_0) \quad (6)$$

The net rate of recombination depends on the presence of electrons in the conduction band and holes in the valence band. Photons can be absorbed in produce new electron-hole pairs. The stimulated emission rate is proportional to the intensity of the optical field, I_{opt}:

$$R_{stim} = g \frac{I_{opt}}{\hbar\omega} \quad (7)$$

where g is the optical gain and $\hbar\omega$ is the photon energy. In the non-radiative recombination process, no photons are emitted. The two main processes in non-radiative recombination are Shockley–Read–Hall (SRH) recombination and Auger recombination. In Auger recombination, excess energy is transferred to another electron in the valence or conduction band (Figure 1). The Auger recombination rate is expressed by the following relation [3]:

$$R_{Aug} = (C_n n + C_p p)(np - n_0 p_0) \quad (8)$$

In the above relationship, C_n and C_p are Auger coefficients. The SRH recombination involves deep energy levels within the semiconductor bandgap, which are created by crystal defects. These defects can trap electrons from the conduction band and holes from the valence band and are considered as recombination centers. Based on simple statistical principles, the net electron transfer rates from the conduction band (R_n) to the valence band (R_p) are expressed by the following relations [1]:

$$R_n = c_n n(1 - f_t)N_t - c_n n_1 f_t N_t \quad (9)$$

$$R_p = c_p p f_t N_t - c_p p_1 (1 - f_t) N_t \quad (10)$$

where c_n and c_p are trapping coefficients, N_t is trap density, E_t is trap energy, and

$$n_1 = N_c \exp[\frac{E_t - E_c}{k_B T}] \quad (11)$$

$$p_1 = N_v \exp[\frac{E_v - E_t}{k_B T}] \quad (12)$$

Under steady state conditions, the carrier flux is constant ($R_n = R_p$) and the net rate of the SRH is expressed by:

$$R_{SRH} = N_t \frac{c_n c_p (np - n_0 p_0)}{c_n (n + n_1) + c_p (p + p_1)} \quad (13)$$

Like the case of electron-hole recombination, the production of electron-hole pairs also requires interaction between other particles. As seen in Figure 2, the energy transfer can be provided by phonons (heat production), photons (absorption), or other electrons. There are several methods to generate electron-hole pairs [3]. If the absorption of photon in a material causes the generation of electron-hole pairs, the created luminescence is called photoluminescence, and if the passage of the electric current through the material causes the generation of carrier,

the resulting luminescence is called electroluminescence.
In semiconductors, photons are produced mainly through electron transitions from the conduction band to the valence band. This transition can happen as spontaneous or stimulate. The emission of stimulated photon creates the optical gain. The optical gain is defined as the growth rate of light intensity (photon density) per length unit of light emission. The optical gain is proportional to the probability that a given photon trap an electronic transition from a higher energy level to a lower energy level. A simple expression for gain is as follows [1]:

$$g_{ij}(h\upsilon)=\left(\frac{q^2h}{2m_0^{\ 2}\varepsilon_0 n_r c}\right)\left(\frac{1}{h\upsilon}\right)\left|M(E_{ij})\right|^2 D_r(E_{ij})(f_j-f_i) \qquad (14)$$

The main parameter in this expression is the momentum matrix element $|M|^2$, which determines the transition strength between two electron levels. In relation (14), f_i and f_j are the probability of occupying the energy level E_i and E_j by electrons, respectively.

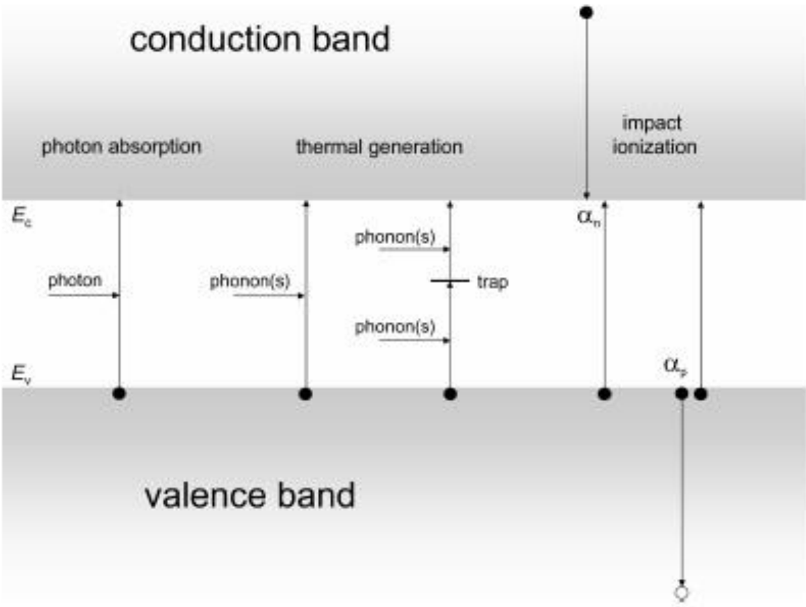

Fig. 2. The main mechanisms of electron-hole pair generation in semiconductors [1].

3. Diodes

In order to study of the diodes, it is necessary to consider the optical properties of their constituent materials. Light sources can be divided into two groups of temporally coherent and incoherent sources, depending on the main mechanism of light production. The basis of the performance of each source is different from each other. Time-incoherent light sources are light emitting diodes (LEDs) that have the characteristics of large form factors and poor coupling efficiency with other optical elements. Time-coherent light sources are also laser diodes (LDs), which, compared to LEDs, have good coupling efficiency with external optical elements and very small form factors for optical power levels. A LD works based on stimulated emission and emits coherent and directional light. In general, it can be said that LDs are not suitable for specific applications where a temporally incoherent radiation and spatial expansion are expected. The basis of the LED is also based on spontaneous emission. This diode emits incoherent light with different wavelengths. A Superluminescent Light Emitting Diode (SLED), like a LD, is based on p-n electrical junction that, when subjected to forward bias, behaves optically and causes amplified spontaneous emission in a wide range of wavelengths. By applying a direct voltage, the injection current is created from one side of the active region of the SLED to the other side. During this process, the light is created due to the spontaneous and random recombination of holes and electrons and then it is amplified by moving along the waveguide of the SLED. The optical performance of SLED is based on an intermediate state between the performance of LD and LED. SLED is an edge-emitting semiconductor light source that can combine the low coherence and wide optical spectrum of LED with the brightness and high power of LD [17]. The optical characteristics of mentioned diodes are compared in Table 1.

Table 1. Comparison of optical characteristics of LED, SLED and LD.

property	LED	SLED	LD
light emission	spontaneous	amplified spontaneous	stimulated
optical spectrum	wide	wide	thin
output optical power	medium	medium	high
optical power density	low	medium	high
optical waveguide	does not have	has it	has it
light emission	all directions	divergence-limited	divergence-limited
spatial coherence	low	high	high
temporal coherence	low	low	high
form factor	large	small	small
noise production	low	low	high
polarization state	random	linear	linear

LD is a way to control the emission of photons by energetic atoms. A material containing atoms in excited states can emit light when electrons move from higher to lower energy levels. This process usually happens randomly and is considered as spontaneous emission. The emitted radiation is incoherent and can travel in all directions. The photon energy depends on the distance of the energy band between the excited and ground states. For a semiconductor, this distance is considered as band gap. This process, which can also happen inductively, occurs when a photon causes the transition of an electron to a lower state. During this process, another photon is emitted. Two photons have the same phase, frequency and direction. The laser is basically an optical waveguide that confined by a mirror with reflective walls in the form of a resonator cavity. Therefore, the propagation of optical modes in the mentioned structure is similar to the propagation of microwave electromagnetic signals. The wavelength of light emitted from LD is determined by the bandgap of the semiconductor material that makes the diode. The laser beam has four important properties, which are: high intensity, directness, monochromaticity and coherence. The laser beam can include any of the frequencies in the range of the mentioned spectrum, with the difference that it has characteristics such as monochromaticity, coherence and high intensity.

In the state of thermal equilibrium of a two-level system where the distribution of electrons between energy states is determined only by thermal excitation, the population density of the upper levels of the valence band is always much greater than the population density of the lower levels of the conduction band. Therefore, the semiconductor normally absorbs light. In order to the semiconductor to amplify light instead of absorbing it, the density of the electron population in the lower levels of the conduction band must be greater than the density of the electron population in the upper levels of the valence band. To create such state (population inversion) in the semiconductor, simultaneous degeneracy between electrons and holes must be created. This can be done by optical or electrical pumping of semiconductor.

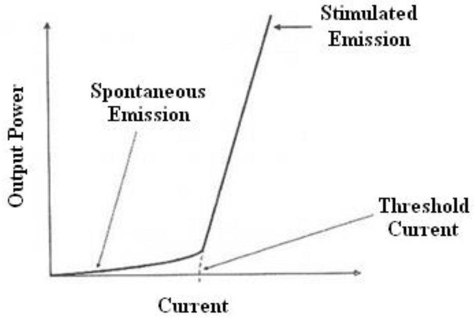

Fig. 3. Light output power as a function of current in a LD [3].

The condition of population inversion is that the stimulated emission rate is more than the absorption rate. In other words, for the population inversion, the difference of the pseudo-Fermi levels must be greater than the energy difference between the two levels which the transition occurs between them. The trapping of carriers in a homogeneous LD is low effective and the active area depends on the stimulated emission and gain. By increasing the stimulated emission rate in the active region, the cavity gain overcomes the losses and the laser operation begins. The injected current created in this case is called the threshold current (Figure 3).

In a LED, and under direct bias conditions, electrons and holes are injected into the n-type and p-type regions, respectively. The increased carrier density leads to the recombination of electrons and holes in the junction and the generation of photons by spontaneous emission [4]. The recombination of these minority carriers with the majority carriers in the p-n junction, takes place near the band gap. The wavelength of the emitted light depends on the energy bandgap of the semiconductor material:

$$\lambda = \frac{1.24}{E_{gap}} \quad (15)$$

In electroluminescence, by applying a strong electric field, electrons are excited from the valence band to the conduction band and emit light when they return to the valence band. Electroluminescence of injection is a very important mechanism in the exciting of semiconductor materials. LEDs are used in computers, digital screens, and also in fiber optic communications. LEDs can be made in two structures: edge-emitting and surface-emitting. The difference between these two types of structures is in the place of light radiation. Light radiation occurs in the edge-emitting structure at the side edge, and in the surface-emitting structure at a certain level above the active region of the diode.

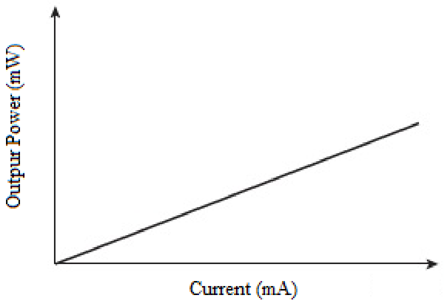

Fig. 4. Light output power as a function of current for a LED.

Figure 4 shows the light output power as a function of current for a LED. As can be seen, the light output power is as a diagonal straight line that increased with increasing current. For this reason, the LED is considered as a linear device. By comparing this diagram with the diagram in Figure 3, it can be seen that this diagram is similar to the linear part of the changes in optical output power versus current in a LD, which is obtained before the start of lasing. Thus, it can be said that a LD acts like a LED before the threshold current.

Figure 5 shows the output spectrum of an AlGaAs surface emitter [5]. In this diagram, the output power is plotted as a function of wavelength. It can be seen, all wavelengths in the range of 0.75-0.87 µm are present in the output spectrum, but some wavelengths have a higher power. This spectrum is measured by passing a certain current through the LED, and when we change the current, the overall shape of the diagram does not change, but the maximum power changes. Also, there may be a slight shift in the wavelength of the peak. The reason for this shift may be related to heating of the device.

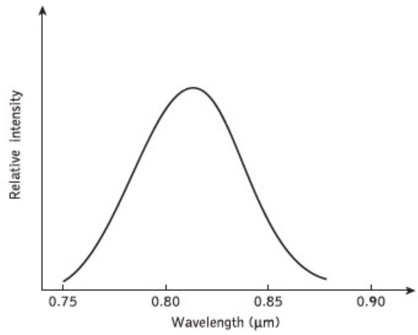

Fig. 5. Output spectrum for an AlGaAs surface emitter with doped active region [5].

The spectral linewidth of a LED at half maximum intensity (full width at half maximum) for a sample operating in the wavelength range of 0.8-0.9 µm at room temperature is typically between 25 and 40 nm. For materials with smaller bandgap operating in the wavelength range of 1.1-1.7 µm, the line width increases to 50-100 nm. By increasing the temperature, the output spectra become wider, and this is due to the greater energy width in the energy distribution of the carriers. The increase in junction temperature affects the wavelength of the emission peak and shifts it. Therefore, in order to prevent of heating up of device, it is necessary to use heat sinks in the diodes.

The external quantum efficiency η_{ext} expresses the average number of emitted photons per injected electron. This efficiency can be written as the multiplication of the internal quantum efficiency and the optical efficiency of photon extraction [1]:

$$\eta_{ext} = \eta_{\text{int}} \times \eta_{opt} \quad (16)$$

Figure 6 shows the internal optical power $P_{\text{int}}(I)$ and the internal quantum efficiency $\eta_{\text{int}}(I)$ as a function of current. The internal quantum efficiency, which is the fraction of photons produced per injected electron, is:

$$\eta_{\text{int}} = \frac{q}{h\upsilon}\frac{P_{\text{int}}}{I} = \frac{I_{spon}}{I_{spon} + I_{nr} + I_{leak}} \quad (17)$$

According to the relation (17), the internal quantum efficiency can be calculated as the ratio of the spontaneous recombination current (I_{spon}) to the total current (the sum of the currents related to spontaneous recombination, non-radiative recombination in the quantum well (I_{nr}) and carrier leakage from the well (I_{leak})). Leakage carriers eventually recombine outside the quantum well. Ideally, a very long half-life (1 μs) leads to inappropriate non-radiative recombination inside the quantum well ($I_{nr} = 0$). As seen in Figure 6, at higher currents as well as higher temperatures, leakage losses increase and efficiency decreases. The internal quantum efficiency is also calculated as a function of carrier lifetime:

$$\eta_{\text{int}} = \frac{\tau_{nr}}{\tau_{nr} + \tau_r}$$

(18)

The optical efficiency of photon extraction η_{opt} expresses the fraction of photons escaped from the device per photons produced internally.

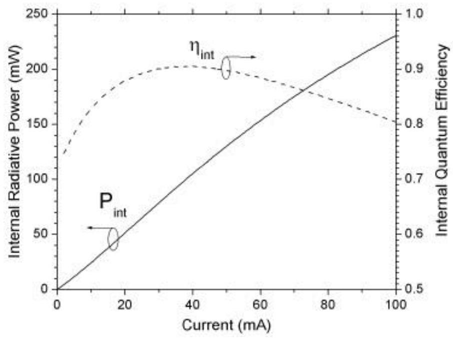

Fig. 6. Internal optical power and internal quantum efficiency as a function of current [1].

Photon escape is mainly limited by total internal reflection. The optical quantum efficiency of the upper surface of a device can be expressed as follows:

$$\eta_{opt}^{top} = \frac{1}{2}(1 - \sqrt{1 - \frac{n_e}{n_s}})(1 - \frac{(n_e - 1)^2}{(n_e + 1)^2}) \quad (19)$$

where n_s is the refractive index of the semi-conductor and n_e is the refractive index of the plastic epoxy. Multiple reflections inside the device and emission from other surfaces lead to a large value for the total optical efficiency. The internal quantum efficiency of the best LEDs has increased values greater than 80% for 450 nm blue LEDs at low current densities [6]. Further improvement of internal quantum efficiency to 100% requires the reduction of non-radiative pathways such as non-radiative recombination in defects and reduction in Auger non-radiative recombination. The high performance of LEDs is limited by some issues such as low internal quantum efficiency, low output power, poor efficiency of cavity injection, high electron leakage, inefficient radiative recombination, and high dislocation density [7]. In addition, when the current injection is high, the loss of efficiency is observed [8].

GaN based LEDs were first introduced by Nakamura et al. in 1990 [15]. The active region of these devices is made of InGaN, which can cover a wide range of wavelengths. Today, in particular, blue and green nitride LEDs are widely used in full-color displays and traffic lights. Due to the low symmetry, the wurtzite system like GaN-based materials exhibits piezoelectric behavior [A]. Macroscopic polarization in materials comprising of the active region of quantum well structures increases the net electric field perpendicular to the plane of the well, leading to the quantum confined Stark effect (QCSE). The blue shift of elctroluminescence in InGaN blue/green LEDs, with an increase in operating current, may be explained by the QCSE resulting from the piezoelectric fields created by the lattice mismatch. At low current density (less than 10 A/cm^2), the efficiency of InGaN/GaN LEDs reaches its maximum value and decreases rapidly with increasing current. This phenomenon (loss of efficiency) is a major obstacle to achieve high power LEDs for illumination applications.

4. Conclusion

The optical performance of light sources, according to the main mechanism of light production, is divided into two categories: coherent and incoherent. A LD emits coherent light based on stimulated emission. Also, the LED operates based on spontaneous emission and causes the emission of incoherent light with different wavelengths. A SLED is an edge-emitting semiconductor light source that can combine the low coherence and wide optical spectrum of a LED with the high brightness and power of a LD. This diode operates based on amplified spontaneous emission. The output optical power of LDs is high compared to LEDs and SLEDs. On the other hand, LED and SLED have a wide optical spectrum, while LD has a thin optical spectrum. At low current densities, the internal quantum efficiency of 450 nm blue LEDs is above 80%.

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